Cranfield University

SCHOOL OF ENGINEERING
Department of Process and Systems Engineering

EngD Thesis

Academic Year 1996 to 2001

S. O'Neill

Hydraulic Optimisation of Service Reservoirs To Maintain Water Quality in Distribution Systems

Supervisor Dr Hoi Yeung

October 2001

Abstract

Water supply utilities worldwide are under pressure to meet stringent water quality and supply demands Service reservoirs (SRs) or treated water storage reservoirs have been built for the dual function of maintaining pressure and providing a buffer of supply. A balance must be sought between operational objectives in order to ensure adequate supply in the event of unforeseen incidents whilst limiting the maximum time between abstraction and the point of use.

Existing reservoirs can have storage times between a couple of hours and several tens of days. The resulting degradation in water quality ensures that it is no longer feasible to focus on point of abstraction treatment as a means of assuring that all customer and legislator expectations are continuously met.

This thesis aims to evaluate the hydraulic design and operation of service reservoirs in the UK and evaluate methods to improve performance.

A generic study of mixing in service reservoirs has been conducted using physical modelling techniques. The segregation of generic groups of reservoirs for modelling was defined after a comprehensive survey of 166 operational full-scale reservoirs was completed. Reservoir groups are defined in terms of shape and aspect ratio. Steady state, transient tests and intermittent flow – "fill and draw" tracer tests were conducted. Step and pulse trace injection techniques were used. Dye tests were conducted for flow visualisation and the results recorded with photographic stills and a digital video recorder.

Water age is quantified in terms of cumulative percentage of injected trace recovery. Flow fractions in terms of dead space, plug flow and mixed flow are quantified for each series of tests using a multiparameter model. Alternative methods of quantification of dead areas are evaluated and discussed. Key reservoir performance indicators are defined and linked to water quality issues.

The results presented have been compiled into a design guide document to enable water utility managers to simply evaluate existing reservoir designs and evaluate potential operational and retrofit options for optimisation. Case studies of full-scale reservoirs applications are presented.

Acknowledgements

I would like to thank Dr Hoi Yeung of Cranfield University for all his help, guidance and continued support throughout the whole of this programme. His previous work has been a great motivational factor in the initiation of this project.

Without the expert guidance of David Crow on the design and commissioning of the physical modelling facility the programme of work would not have been completed.

I would also like to thank John Mapes of Cranfield School of Management for his guidance on business and operational management issues.

There are a number of key individuals at North West Water without whom this work would not have been completed and I would like to thank them in turn.

Geoff Taylor, formerly of North West Water for all of his guidance, mentoring and personal support throughout the whole of this project and my time at North West Water. It is greatly appreciated.

Rene Frost for spending most of his working days setting up the models and running the programme. Without his hard work the programme of modelling completed would have been seriously curtailed .

Ian Skilling for all his work on the model control programme and support during the project. Graham Garwell and Peter Williams for their help optimising the conductivity control algorithms.

Peter Womersley for his strategic support of the work and his key role in ensuring that the results and recommendations were adopted across the company.

My colleagues in the former Technology Development Team, for all their support.

Finally I would like to thank my husband Tom and son Harry for always being there when I had inclinations not to submit.

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1 Introduction

Water supply utilities worldwide are under pressure to meet stringent water quality and supply demands using infrastructure that can be up to 100 years old. Managers must balance treatment and operational objectives in order to ensure adequate supply in the event of unforeseen incidents whilst limiting the maximum time between abstraction and the point of use.

Service reservoirs (SRs) or treated water storage reservoirs have historically been built for the dual function of maintaining pressure and providing a buffer supply. Existing reservoirs can have storage times between a couple of hours and several tens of days. The resulting degradation in water quality makes it no longer feasible to focus on point of abstraction treatment as a means of assuring that all customer and legislator expectations are continuously met.

The objectives of the thesis are therefore to:

- Evaluate the hydraulic performance of service reservoirs as designed and operated in the UK.
- To identify key areas of hydraulic performance which can affect storage water quality and compliance.
- Evaluate potential cost effective improvement strategies
- Provide business tools to ensure enhanced future design of storage reservoirs and facilitate company adoption of improvement strategies.

Chapter 1 begins by outlining the history of water treatment. This is followed by an in depth discussion on the microbial, chemical and physical effects on treated water upon storage and the resulting regulatory and financial implications.

Chapter 2 outlines the objectives of the Thesis in some depth and provides a description of the subsequent chapters.

1.1 The History of Water Treatment and Supply

Throughout the United Kingdom and most of industrialised world people turn on their taps with the expectation that they will get wholesome and abundant drinking water. The service is something they consider not only to be their right, but they may also be entitled to financial compensation if it fails.

So it may be difficult to imagine that today in certain parts of the world the search and transport of safe drinking water can be the daily occupation for thousands of people. This is not dissimilar to the human search for pure water in prehistoric times. Archaeology relates that ancient civilisations developed around water sources. As populations grew the need to augment the water supply was met by bringing in supplies from further afield using some of the earliest forms of distribution system.

Durrant (1954) described some of the earliest reports of water distribution, which date back to 3000 BC in Nippur, Sumeria, where the remains of a centralised supply system that directed fresh water into palaces and diverted wastewater away were discovered.

Highly advanced systems were built as early as 2500 BC. These incorporated water collection, transport systems including canals and aqueducts, as well as surface and underground storage vessels – the first service reservoirs. One example, built by the Harrappans at Mohenjo-daro in the Indus River Basin, showed the used of burnt bricks for lining wells and storage vessels. Hollowed out trees were also used as pipe materials - hence the common terminology of "trunk" mains.

It is evident that the Ancients had an advanced understanding of the implications to health of water quality and treatment. Baker, 1949, described a Sanskrit inscription on an Egyptian wall dating back to 2000 BC which described the process of water purification as

> *"boiling in copper vessels, exposing to the sun, filtering through charcoal and cooling in an earthen vessel"*

Domestic point of use treatment was advocated on the walls of Egyptian tombs dating from the reign of Amenhotep II (1447-1420 BC) and Rameses II (1300 to 1223 BC). The inscriptions depicted the settlement of sediments in bottles and siphoning using wicks. They also show that the basic principles of modern water treatment were being used in everyday kitchens.

The ancient Greeks made use of the natural cement deposits available, using concrete, clay and masonry in the construction of more extensive water distribution systems. This led to more strategic and widespread organisation of communal water supplies. They were the first to build long distance high-pressure water mains. A pressurised aqueduct was installed at Pergamum, Asia Minor in about 200BC. This carried water from a storage reservoir at 1220 ft to a cistern at 369 feet, which fed a network of masonry lined channels and clay pipes terminating in secondary cisterns, streets and individual houses. The pipe lengths were joined by cement and often internally glazed for waterproofing.

The Romans built the most extensive water distribution systems during that period. Having a fondness for public baths and fountains, the supply of water from the river Tiber and local spring sources became inadequate. This demand led to the construction of large aqueducts to bring in suitable water supplies. The first of the great aqueducts, the "Aqua Appa" was built in 312 BC. By the year 305 AD it had expanded to comprise a system of 15 aqueducts with a combined length of 359 miles.

The Roman distribution systems are not dissimilar to present day systems. The large aqueducts discharged into large service reservoirs, which in turn gravity fed water through a network of lead pipes to smaller cisterns, public fountains and bathing houses. Most of the population would get their water from the public fountains.

The Romans understood the importance of sanitation systems and documents of the time refer to the use of water for flushing of drains and sewers. The first reported Engineering Document on water supply was written by Sextus Julius Frontius in AD 98 who was the commissioner for water supply in Rome. In these he describes the use of settling reservoirs and basic grit channels at the head of one of the great aqueducts.

The quantity of water delivered to Rome has been estimated as 50,000,000 gallons a day. Or about 50 gallons per person per day.

The fall of the Roman empire marked the end of an era in water and wastewater treatment and distribution. It was not until the 16^{th} Century that Europe began to recover and small private companies began to appear. Water filtration on a large scale was introduced in London in 1829, when James Simpson who worked for Lambeth and Chelsea water company introduced slow sand filtration. In 1848 parliament created the Metropolitan Commission of Sewers. A cholera epidemic later that summer and 14,600 deaths empowered the commission to improve water and wastewater systems in London. Governments began to look at centralised water and wastewater supply systems as a means of protection of public health.

1.2 Water Treatment and Supply Today

The main purpose of drinking water treatment is to provide a sufficient supply of water that conforms to the individual country's drinking water regulations and is therefore wholesome. This is achieved by installing a series of treatment processes or barriers, for the removal or reduction of contaminants, especially pathogen bacteria. The conventional technologies adopted in the water industry rely upon multiple barriers - no single barrier is considered reliable to remove all pathogens. With the increase in application of membrane technologies this convention is being challenged. Generally, the most essential barrier is considered to be the disinfection process. In addition it is usual to try to maintain a residual disinfectant to assure integrity throughout the subsequent distribution system.

The demand for public water supply varies seasonally, daily, hourly. Higher water demand occurs in the summer. Some changes in demand can be accurately forecast, while others cannot, for example when thousands of people get up to make tea during the interval of a television blockbuster.

To balance such varying demand would be impossible to achieve even with modern treatment plant control capability and booster pumping stations. In addition most conventional treatment processes do not respond well to rapid increases or decreases in flowrate. Therefore treated water storage or service reservoirs are required in the distribution systems to ensure that adequate supply can be guaranteed, even with unforeseen peaks in demand.

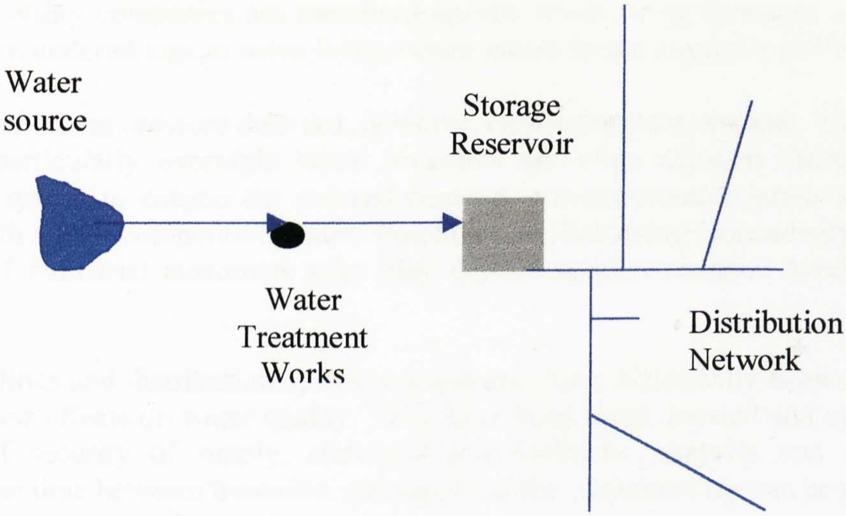

Figure 1.1 - Simplified Schematic of Water Supply System

A simplified system comprises water abstraction, treatment and distribution stages and is depicted in Figure 1.1. The water distribution system in the UK is somewhat more complex. The network is divided into discrete zones called district-metering areas (DMA's). The sources of water into each district and interdependencies of supplies between districts are assumed to be known and well defined. The flow into each DMA is recorded using a data logger connected to a district flow meter. For many utilities night time flow data gathered from the meters is the main source of leakage information.

A DMA may receive sources of different quality compliant water and contain multiple storage reservoirs. As companies increase the flexibility to pump water around the distribution network and with escalating competition, storage reservoirs have and will provide convenient points in the network to add or take off water supplies.

1.3 Service reservoirs

Service reservoirs are built to provide the dual function of balancing supply with demand and the provision of adequate head pressure throughout the distribution network. The majority of water utilities guarantee to maintain a minimum water pressure of 7m static head. United Utilities, which supplies a population of 7 million in the north west of England has a policy to compensate customers if they fail to provide this twice per month. The compensation per customer per incident is £10. One can calculate the costs of a significant, prolonged fall in pressure due to a major burst or source water contamination incident and hence the value of increased security that storage reservoirs may provide.

To give an indication of the number of storage reservoirs employed, United Utilities distribution system covers 14,000 square kilometres incorporating 418 service reservoirs.

All the UK utility companies are measured against levels of performance and can be fined or given undertakings to solve low pressure issues by the regulator (OFWAT).

Ensuring a minimum pressure does not, however, ensure constant pressure. The pressure will vary, particularly overnight when pressures are often adjusted throughout the distribution system to counter the reduced demand, prevent pressure bursts and reduce leakage. With stiffer competition water companies are becoming increasingly aware of the needs of industrial customers who may depend upon a constant level of water pressure.

Storage facilities and distribution system components have historically been considered neutral in their effects on water quality. They have been sized, located and operated on the basis of security of supply, structural and hydraulic integrity and reliability. Therefore, the time between treatment and supply to the customers tap can be excessive.

This may have been acceptable in the past as there was limited capability to measure the effects of storage. However, with increasingly stringent regulations both at the point of treatment and use, the adverse effects of prolonged storage have become increasingly apparent (Kennedy, 1991, Clark, 1992, Grayman 1993, Kennedy 1993, Mau 1995, Mau 1996). Utilities are no longer focussing solely on water treatment works optimisation as the means of ensuring compliance at the point of use.

1.4 Water Quality

In order to understand the potential implications of service reservoir design and operation on water quality in distribution, it is important to understand under what terms water quality is defined and measured. Also, what are the implications for the customer, and the operational and financial implications for the provider, if water quality parameters are exceeded? Individual countries and states have different legislative requirements and target levels for contaminants some more stringent than the World Health Organisation Guidelines.

Certain contaminants will be reduced to acceptable levels at the water treatment works and concentrations or the form of the contaminant will not be altered as a result of passage through the distribution network or storage in the reservoir. These are not discussed here: of greater interest is the detrimental effects on quality as a function of storage.

Kirmeyer et al (1999) categorised the problems associated with storage as chemical, microbiological and physical. They point out that many quality problems resulted from a complex relationship between all three. These categories will be used here.

1.4.1 Chemical

There are many quality issues that result as a function of changing chemistry on storage.

1.4.1.1 Disinfectant by product formation

The nature of the disinfectant dictates the disinfection strength. In 1967 Morris presented a table of germicidal concentrations giving 99 per cent -2 log inactivation within ten minutes contact time. From this Morris derived a lethality coefficient, λ.

$$\lambda = {}^{0.46}\!\big/_{C_{99:10}} \qquad 1.01$$

Where **C** is the concentration of chlorine compound in mg/l. The values of lethality coefficient λ calculated are shown in Table 1.1 below

Species	*Enteric Bacteria*	*Amoebic Cysts*	*Viruses*	*Spores*
HOCl	20	0.05	1.0 up	0.05
OCl^-	0.2	0.0005	<0.02	<0.005
NH_2Cl	0.1	0.02	0.005	0.001

Table 1.1 - Lethality Coefficients

This illustrates that the strength of each disinfectant species is different, in this instance chlorine in the form of hypochlorous acid is more effective than monochloramines or the hypochlorite ion.

The disinfectants most frequently used in the water industry are chlorine, chlorine dioxide, chloramines, ozone and ultraviolet radiation. The role and level of usage of these disinfectants vary widely. To achieve the same disinfection efficacy different concentrations and contact times are required (White, 1986).

In addition, the oxidising ability of each chemical is different. Consequently some of the chemicals are used for other functions within the treatment process. For example ozone may be used for breakdown of pesticides and chlorine is commonly used at high pH for manganese precipitation.

Each disinfectant species has the potential to form a range of disinfection by-products with distinct toxicology. By-products that are a major concern in the water industry are trihalomethane compounds, THMs. This is because chlorine is the most widely used disinfectant as it provides continued disinfection in the form of a residual.

Trihalomethanes include trichloromethane - chloroform, tribromomethane, dichlorobromomethane, and dibromochloromethane. They are formed in the presence of chlorine and organic precursor molecules. Chloroform is thought to be a human carcinogen (Attias, 1995).

The current UK Drinking Water Regulations specify that the mean concentration of total THMs (the sum of all trichloromethane, dichlorobromomethane, dibromochloromethane and tribromomethane) measured over a three month period should not exceed 100 μg/l at the customer's tap.

Future changes in the legislation have been anticipated for some time following the reduction in standards in the USA. The disinfection by-products rule D/DPB reduces the total THM legislative level from 100 to 80 μg/l in stage I, and 40μg/l in stage II. In addition haloacetic acids (HAA's) are regulated to 60μg/l in stage I, and potentially 30μg/l in stage II.

Catchment management strategies as discussed by Pattinson, (1994) are employed to reduce raw water colour. Even with best practice approaches to catchment management, climate change effects in recent years have resulted in exponential increases in raw water TOC concentrations in some parts of the country, resulting in THM non-compliance in areas fed by three stage water treatment works. It should be noted that waters that have low colour (< 10 Hz) can still have significant THM formation potential.

Numerous factors affect the rate of formation, the concentration and the nature of trihalomethanes formed, both during treatment processes and in the subsequent distribution system. These include variables such as the chlorine concentration, the chlorine species present, the type and concentration of organic precursor molecules, the temperature, the contact time or water age, bromide concentration and pH (Regli, 1993).

As the storage time is increased, the THM formation increases. Therefore large increases in THM's can be associated with service reservoirs with long detention times. The practice of re-chlorination to control biological growth also increases the THM formation. In addition any increase in pH as a function of storage will result in an increase in the fraction of free chlorine that exists in the form of the hypochorite ion, which also increases THM formation.

The focus on reduction of THM's in distribution has been on the improvement of removal of THM precursors from the source water via coagulation. However, low molecular weight organics can be difficult to remove with conventional coagulation. Therefore looking at the source of treatment as a means to curb THM formation is increasingly leading to the use of capital and operational cost intensive solutions such as ozone followed by GAC.

The other strategies by which the THM levels in distribution can be reduced are to:

- **reduce chlorine usage.** This is an unlikely scenario: residual concentrations are generally set in the UK to assure bacteriological compliance and offset residual losses.
- **Optimise distribution pH (pH 7)** This is certainly feasible and results in enhanced disinfection. A full scale trial of reducing pH throughout the distribution system of one utility for a period of one month did not however result in statistically significant reduction in the THM's at the end of the distribution chain.

- **Optimise the hydraulic performance of service reservoirs to reduced water age.** This is a method reducing THM's that can be addressed rapidly without major capital requirement.

Figure 1.2 shows a schematic of a UK distribution system network with the associated THM compliance data. The area receives a blend of water from a surface water treatment plant (TOC < 4mg/l) and two borehole sources (TOC <1 mg/l). There are four service reservoirs within the network. Reservoirs 1 and 2 have a nominal retention time of 1 day and reservoirs 3 and 4 have nominal retention times of 4.5 and 5.8 days respectively.

It is evident that zones 3 and 4 fed by these reservoirs are non-complaint for THM's. Monitoring THM levels in the water entering and leaving the reservoir showed that the THM concentration increased by approximately 50 μg/l

- **SR 3:** Average THM increase 90 to 141 μg/l
- **SR 4:** Average THM increase 87 to 141 μg/l

Nominal retention times are based upon the operational volume of the reservoir divided by the average daily flowrate, however they do not indicate the actual distribution of age of water in the reservoir.

	% non-compliance for THM			
Zone	**1997**	**1998**	**1999**	**Average**
1	0.00	8.33	0.00	2.78
2	0.00	0.00	0.00	0.00
3	42.86	66.67	46.15	51.89
4	38.46	75.00	38.46	50.64

Table 1.2 - THM non-compliance data for a UK water distribution zone.

Optimisation of the distribution system in terms of reducing water age by improved reservoir management; mixing and turnover can have a significant effect without incurring major capital or operational costs. This potential route to achieving compliance can often be ignored. This is not helped by the fact that although various models have been developed to predict THM formation for specific waters and treatment conditions, the majority require extensive calibration to determine site or system specific constants.

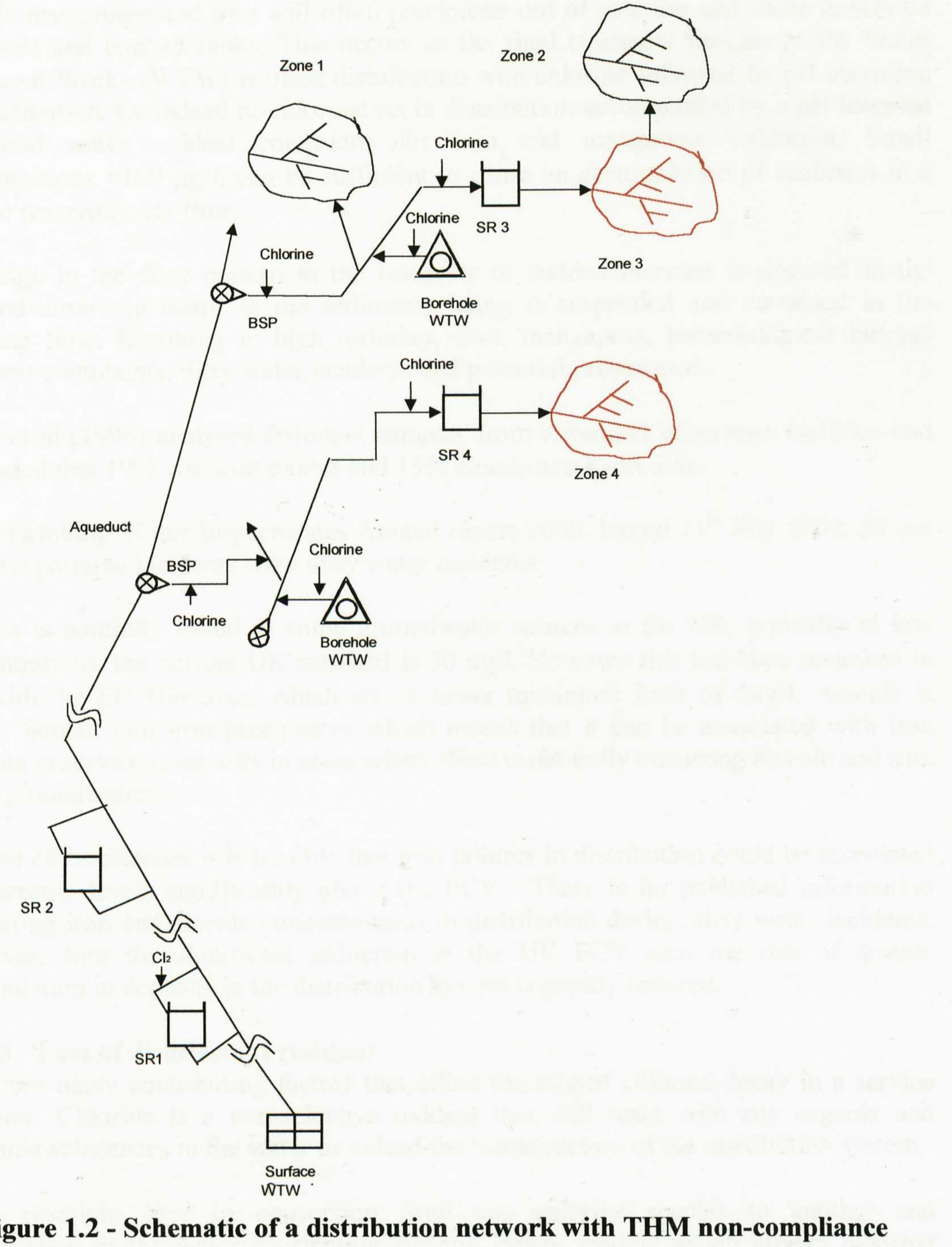

Figure 1.2 - Schematic of a distribution network with THM non-compliance

1.4.1.2 Deposition of iron, manganese and arsenic

Soluble manganese and iron will often precipitate out of solution and settle in service reservoirs and contact tanks. This occurs as the final treatment process at the Water Treatment Works (WTW) is often disinfection with chlorine followed by pH elevation for distribution. Or indeed re-chlorination in distribution accompanied by a pH increase in stored water - ideal conditions for iron and manganese oxidation. Small concentrations <100 µg/l, can be sufficient to cause an accumulation of sediment in a storage reservoir over time.

A change in the flow pattern in the reservoir or sudden increase in demand in the supplied zone can result in the sediments being re-suspended and entrained in the outgoing flow. Resulting in high turbidity, iron, manganese, bacteriological failures customer complaints, dirty water incidents and potential prosecution.

Block et al (1996) analysed sediment samples from a number of storage facilities and concluded that 19% was iron oxides and 15% aluminium hydroxide.

In the Drinking Water Inspectorates Annual report 2000, Issued 11th July 2001, 58 out of 109 reportable incidents were dirty water incidents.

Arsenic is naturally found in some groundwater sources in the UK, typically in low concentrations, the current UK standard is 50 µg/l. However this has been reviewed in line with the EC Directive, which sets a lower maximum limit of 5µg/l. Arsenic is readily bound with iron precipitates which means that it can be associated with iron deposits in service reservoirs in areas where there is naturally occurring arsenic and iron in the groundwater.

In these circumstances it is feasible that iron failures in distribution could be associated with arsenic levels significantly above the PCV. There is no published information correlating iron and arsenic concentrations in distribution during dirty water incidents. However, with the significant reduction in the UK PCV then the risk of arsenic accumulation in deposits in the distribution system is greatly reduced.

1.4.1.3 Loss of disinfectant residual

There are many contributing factors that affect the rate of chlorine decay in a service reservoir. Chlorine is a non-selective oxidant that will react with any organic and inorganic substances in the water or indeed the infrastructure of the distribution system.

These reactions lead to conversion from one chlorine species to another and consumption in the water distribution system. Hence models which predict chlorine decay have sometimes had limited success for site specific application, unless factors such as chlorine demand of the water itself – organics, inorganics, sediment deposits, microbiology, exposure to sunlight, materials of construction and exposed / wetted surface area can be taken into account. In a storage tank the ratio of volume to surface area in contact with the vessel is much larger than for a pipe system and therefore losses due to material / corrosion can be less significant.

Vasconcelos et al (1995) conducted a study to evaluate four chlorine decay models at five water utilities using jar tests. For each model there was a wide range of fitted coefficients in line with the differences in source water. Sylvana (1997) evaluated pilot scale laboratory pipe system to simulate distribution system chlorine decay mechanisms. Again, the complexity of the water quality issues in the distribution network results in limited applicability to a full scale more complex system.

Whilst Biwas et al (1993) noted that the numbers of dead end pipe zones in use contributed significantly to the loss in chlorine residual and poor water quality in distribution. Schade et al considered that pipe dead end zones constituted a large proportion of the distribution system.

Boulos in 1996 used fluoride as an inert tracer to understand the dynamics of mixing and free chlorine concentration in an operational reservoir. His results supported the hypothesis of stratification or partitioning in reservoirs as a result of poor mixing. Kennedy et al (1993) conducted chlorine concentration profiling studies on a number of full scale circular reservoirs with common inlet / outlets. The reservoir with a depth to diameter ratio of 0.4:1 showed variation in chlorine concentrations in the lower two thirds of the tank. The general conclusions were that residuals were more uniform and water quality appeared to be best when water volume changes were maximised.

A long detention time can allow the disinfectant residual to be completely depleted. (North West Water study)

Loss of chlorine residual and poor control are the most common problems associated with storage water reservoirs.

1.4.1.4 Taste and odour

It had long been established that chemical decomposition of settled deposits can lead to taste and odours. Burlinghame and Anselme (1995) evaluated a number of the effects of storage on taste and odours. Chlorine residual can render water more palatable by disguising the underlying taste, which may then become apparent as the chlorine residual decays. The loss of chlorine residual can lead to bacteriological growth that also results in taste and odours. Montiel et al (1987) linked the strong musty taste in Paris water to fungi that were transforming chlorophenols to chloroanisoles.

Taste complaints can arise from the transformation of monochloramines to dichloramines as reported by White (1986). Monochloramines can be formed by the chlorination of ammonia in the source water at a ratio of up to 4.1:1 free chlorine to ammonia. If the water is re-chlorinated as is common at storage reservoirs, then the chlorine to ammonia ratio can increase and monochloramines are transformed to dichloramines which have a sharp, bleach like odour.

Hydrogen sulphide with its associated rotten egg smell can be formed in reservoirs when sulphate ions, sulphide reducing bacteria, metal corrosion products or decaying organic matter together with low dissolved oxygen concentrations are present. Pettie, (1990) concluded that the detention time in the reservoir was a contributing factor to the concentration that was produced.

1.4.2 Microbiological

An extensive variety of pathogenic micro-organisms can be found in source waters. These include bacterial spores, protozoan parasites and viruses. The micro-organisms of most concern are transmitted by the faecal - oral route: enteric pathogens

Instead of monitoring for all species of possible micro-organisms, a practical approach is taken to monitor specifically for indicator organisms. Detection of any of these organisms indicates the presence of faecal contamination and therefore the potential presence of enteric pathogens. The micro organism selected for monitoring and measuring compliance are *Escherichia coli* and total coliform counts. Most strains of *E. coli* themselves are harmless, however they indicate the possible presence of other enteric pathogens.

E. coli and Total coliforms counts are the current means of verifying bacteriological water quality and the method against which compliance is established. The compliance target is zero viable coliforms per 100ml of water. The UK Water Quality Regulation expect 100% compliance with this standard at the outlet of Water Treatment plants and 100% compliance for *E. coli* and 95% compliance for total coliforms at service reservoirs.

Increases in adherence to these standards has unquestionably been reflected in a reduction in outbreaks of waterborne disease. Richards (1981) initially raised concerns upon the use of a standard based solely upon the presence of faecal indictor bacteria.

Escherichia coli are very susceptible to disinfection even with the weakest of disinfectant species. Therefore the efficacy of a disinfection process for the reduction of *E. coli* does not represent its effectiveness for elimination of more resistant pathogens such as protozoan cysts (for example *Giardia* and *Cryptosporidium*), virus or other species of bacteria which have higher resistance to oxidants. This has been highlighted by a number of incidents, for example the incidence of gastro-enteritis in Perth reported by Burke (1984), which was caused by *Aeromonas spp.* Chemical treatment and chlorination achieved only a temporary reduction in numbers in the treated water, whereas no *E. coli* were found in the distribution system beyond the service reservoir and coliforms were rarely present.

The interpretation of zero viable coliforms in 100mls actually indicates <1 coliform in 100mls which could indicate the presence of nine in one litre or one in a million litres. While a confirmed failure of 1 coliform in 100ml may seem to be a small degree of contamination, it is not feasible to replicate such a result with human error or contamination. A failure of this nature therefore indicates that viable bacteria are present in the system. Heterotrophic plate counts are also used as an indicator of microbial quality and changes in levels can indicate a deterioration in the source water quality, regrowth or a contamination event.

Generally when a disinfection failure is noted the water is already in supply. Therefore new methods are required for the detection of *E coli* that are cost effective and reduce the length of time to achieve a positive result. Fricker (1998) described a method for the rapid detection of total coliforms and faecal coliforms. However, more than 9 h was required for samples containing less than 10 cfu/ml hence the turnaround time is probably still too long to obtain a positive result within a working day.

Strategies which have been adopted to improve bacteriological compliance and water quality at the outlet of service reservoirs have included the covering of reservoirs, the binding of soil at reservoir margins, protection against frost and the problems associated with condensation. In addition improvements in the design of vents have been recommended by such as Baur (1985) and Kirmeyer (1999). Engineering improvements such as these have been introduced to prevent the ingress of atmospheric pollution.

These have been adopted as standard practices in the United Kingdom where there are now very few uncovered treated water reservoirs. Many utilities have adopted the practice of flooding reservoir roofs to check for ingress during scheduled cleaning.

In the United States by contrast a number of major cities are supplied from very large uncovered reservoirs. These represent a large risk of faecal contamination from wildlife such as nesting birds and gulls as highlighted by Lippy (1976). A number of outbreaks of gastro-enteritis have been shown in epidemiological surveys to be attributable to uncovered treated water reservoirs.

Despite the majority of reservoirs being covered and protected against ingress, due diligence is required in inspection and maintenance of reservoirs. Five deaths and several hundred cases of illness were reported by Atkinson (1995) to be attributable to the presence of dead birds and faeces in a covered reservoir in Missouri.

Where there is no direct form of ingress bacteriological failures still occur at the outlets of service reservoirs and in the subsequent distribution system. Between 1992 until 1999 a not a-typical UK utility had 218 storage reservoirs with confirmed bacteriological failures. During an eight month period during 1999, 41 reservoirs had confirmed bacteriological failures with 6 failing compliance for confirmed *E. coli* incidents.

The sampling frequency is typically one per week, therefore statistically there is a reduced probability of failure when compared to the frequency of monitoring of water treatment plants. In addition the percentage compliance required for Total Coliforms is relaxed to 95%. Nevertheless there are still a number of reservoirs that periodically fail this compliance standard.

1.4.2.1 Bacterial re-growth

Maurice Le Chevalier (1990) conducted an extensive literature review of the sources and causes of microbial growth in the distribution system. From his findings he concluded that the presence of a chlorine residual did not preclude the survival of coliforms and that bacteriological growth was linked to the availability of assimable organic carbon. This was evident especially in parts of the distribution system where the flow rates were very low. It is therefore feasible that coliforms could survive and proliferate in areas of very slow moving or stagnating water in service reservoirs.

Smith et al (1990) identified a number of factors that were favourable to microbial growth, including water temperature, BDOC, nutrients, corrosion products, disinfection practices and hydrodynamics. Volk and Jorret (1994) went one step further, defining thresholds values and concentration for microbial growth.

Amblard (1996) attempted to evaluate this effect by cleaning a service reservoir and monitoring its bacteriological performance when it was returned to service. The raw water was surface derived and treated with Ozone and GAC. The concentration and type of micro-organisms entering the reservoir and within the reservoir itself were monitored over time. In this instance, chlorine was not initially used as a disinfectant and there was no chlorine residual present in the treated water. Perhaps unsurprisingly, a functional ecosystem was established in the reservoir which resulted in a proliferation of micro-organisms in the system. The number of coliforms only fell steeply when free chlorine was added and the residual level increased. This work shows the importance of maintaining a disinfectant residual to reduce the potential of bacteriological growth. It does not, however, address the risk of growth in chlorinated reservoirs.

In contrast Shoenen (1992), devised a simple laboratory experiment to determine the susceptibility of waters to coliform re-growth or colonisation. The experiment involved treating three different source waters, chlorinating them and storing the samples in three different types of containers for six weeks. These included a 400m3 service reservoir, a plastic barrel of 1m3 capacity and several 1 litre glass bottles. Results showed that re-growth and colonisation was possible. In this instance it was concluded that the concentration was more a function of water movement and the nature of the storage container rather than the raw water. The work shows the potential for stressed micro-organisms to recover and re-colonise as the chlorine residual decays. This supports the hypothesis that water quality will deteriorate and chlorine residuals reduce in areas of stagnant water. However, in reality reservoir and distribution networks are not batch but continuous or semi-continuous flow systems. Hence some degree of diffusion of chlorine species into "dead areas" might be anticipated. However as shown by Kennedy et al (1993) stratification of chlorine residuals does occur.

Mark LeChevallier (1998) addressed the ability of *Mycobacterium avium* complex to form and multiply in biofilms. They have a broad antibiotic resistance and have been linked to water related disease outbreaks in Boston and San Francisco reported by Haas et al (1983), Fischeder et al (1991) Glover et al (1994) and Von Reyn et al (1993). The work indicated that in the biofilm they were five times more resistant to free chlorine than Giardia.

The issue of risk of coliform proliferation in chlorinated systems and "dead areas" in service reservoirs is difficult to quantify with confidence by laboratory tests. Quality sampling of water columns within service reservoirs has been limited by the safety and structural constraints of gaining access to appropriate sampling points. In instances where no online water quality data exists, the only evidence that stratification is occurring and potentially affecting treated water quality is provided by the rapid fluctuations of chlorine residuals on the outlet of the service reservoirs.

Bacteriological and water quality data from within storage facilities is critical to evaluating the risk of bacteriological non-compliance resulting from poor mixing. If the risk is not evaluated then the cost of improved mixing cannot be equated to any benefit or quantified risk reduction. The amount of capital or operational expense that is justifiable to reduce the risk therefore becomes difficult to determine.

1.4.2.2 Nitrification

Nitrification is a two-step biological process that involves the conversion of ammonia to nitrite and from nitrite to nitrate by bacteria. It occurs in distribution systems where chloramination is practiced or where source waters contain concentrations of ammonia.

Nitrification in the distribution system can have numerous quality effects such as reducing the chloramine concentration and increasing the concentrations of both nitrate and nitrite. As it is a biological process, the heterotrophic plate counts increase significantly.

1.4.2.3 Cryptosporidium

During the next three years water utilities in the UK will be investing several hundred million pounds in providing adequate protection of water supplies against *Cryptosporidium parvum*. In line with recommendations given by the Badenoch (1990), Badenoch (1995) and Bouchier (1998) expert group reviews.

Cryptosporidium parvum is a protozoan parasite associated with gastroenteritis in humans. Symptoms include prolonged diarrhoea, abdominal cramps, vomiting and fever. The severity of the symptoms can be dependant upon the ingested number of oocysts, the virulence of the strain of crypto and the condition of the individual's immune system as discussed by Crawford et al. (1998) and Smith (1992). A waterborne outbreak in Milwaukee, USA resulted in thousands of individuals becoming infected and several immuno-compromised individuals deaths.

The oocysts can be transmitted via the faecal oral route and via drinking water supplies. They are endemic in the natural environment and in aquatic ecosystems as indicated by Rose et al (1988) and Svoboda (1997) and occur in large numbers in the faeces of lambs and calves. A survey in the North West of England conducted on feeder streams to surface water reservoirs showed that 38% of the samples contained *Cryptosporidium*. This was considerably higher than the 5% found during routine samples taken at treatment plant intakes.

Early emphasis during the 1990's was on catchment management and reducing the risk of contamination of the water supplies, obviating the need for expensive treatment processes (SOAEFD (1992), MAFF (1991)). However regulations in the Unites States have moved towards certification of treatment processes for log removal of cyrptosporidium sized particles and a requirement for inactivation. The current leglislation in the UK is based upon continuous monitoring of *Cryptosporidium* in certain waters with a standard of <1 oocyst per 10 litres.

Inactivation is difficult to achieve. During the past 5 years numerous investigators have evaluated the individual and sequential effects of a number of disinfection and advanced oxidation technologies for Crypto inactivation with varying success. Oppenheimer (1998) reported on the CT requirements of *Cryptosporidium* oocysts seeded into natural waters and exposed to disinfectants either alone or in combination. She reported that with doses that could be achieved in distribution systems, involving chlorine and chloramine, a 0.5 log inactivation could occur. To achieve higher log removals CT values in the order of 8000 mg/L/min would be required. This was supported by the work of Finch et al (1998) where studies suggested that for both *Giardia* and *Cryptosporidium* a 0.5 to 1 log unit increase in inactivation would be possible if disinfectants were used in combination rather than on their own. Various authors including Furst (1998) and Huffman (1998) have reported higher inactivation levels with high intensity UV disinfection

Cryptosporidium is neutrally buoyant and therefore it may be considered to act as an inert tracer in the distribution system. Hence in a closed distribution system the numbers passing into distribution will equal the numbers at the customers tap. Not every individual exposed to viable oocysts will become ill. The rate of onset and severity of the illness are a function of numbers ingested, degree of immunity and virulence of the strain. Hence it is incorrect to assume that the performance of a storage reservoir between the point of contamination and the customer will have a negligible impact on the scale and timing of the incident.

1.4.3 Physical

Where localised fluid velocities in reservoirs are low, particles in suspension such as lime, precipitated metals and corrosion products will settle to form sediments. Not only do these sediments lead to eventual water quality issues as previously discussed, they add a significant operational cost burden in terms of reservoir cleaning. Many UK utilities have a rolling programme for cleaning each reservoir at least once every five years. The sediment can be categorised as chemical waste, which may then require disposal to landfill.

During the period that the reservoir is out of service, the water will have to be diverted through an alternative route, which can result in increased risk of security of supply. The time taken to clean a reservoir is initially estimated, however the actual time required is dependent on the structural condition upon inspection, and the volume of settled deposits, which can often be considerable. It may take several months to be able to put the reservoir back into supply.

Burlingham and Brock (1985) reported the occurrence of insect and worms in storage tank sediments, which have been related to midge fly larvae and worms in drinking water at customers taps.

1.5 UK Water Industry Stakeholders

The UK water industry was privatised in 1989. The UK regulated water companies are not operated with the same freedom as other public companies. It is important to understand who the key stakeholders are and the business process that is followed when balancing the regulatory and water quality pressures with the expectations of shareholders.

At privatisation the British Government established a number of industry policeman, shown in blue, Figure 1.3.

1.5.1 The Drinking Water Inspectorate (DWI)

DWI is responsible for ensuring compliance and due diligence with respect to drinking water quality legislation set out in the Water Supply Act 1989. The DWI review existing quality targets and compliance those quality targets, and set the schedules for compliance with new legislation. They have the power to issue enforcement actions, stipulate treatment requirements, investigate incidents and initiate prosecutions if deemed necessary.

1.5.2 The Environment Agency

The Environment Agency regulates and enforces water quality standards in inland, estuarial and coastal waters. It grants and oversees abstraction licences and discharge consents.

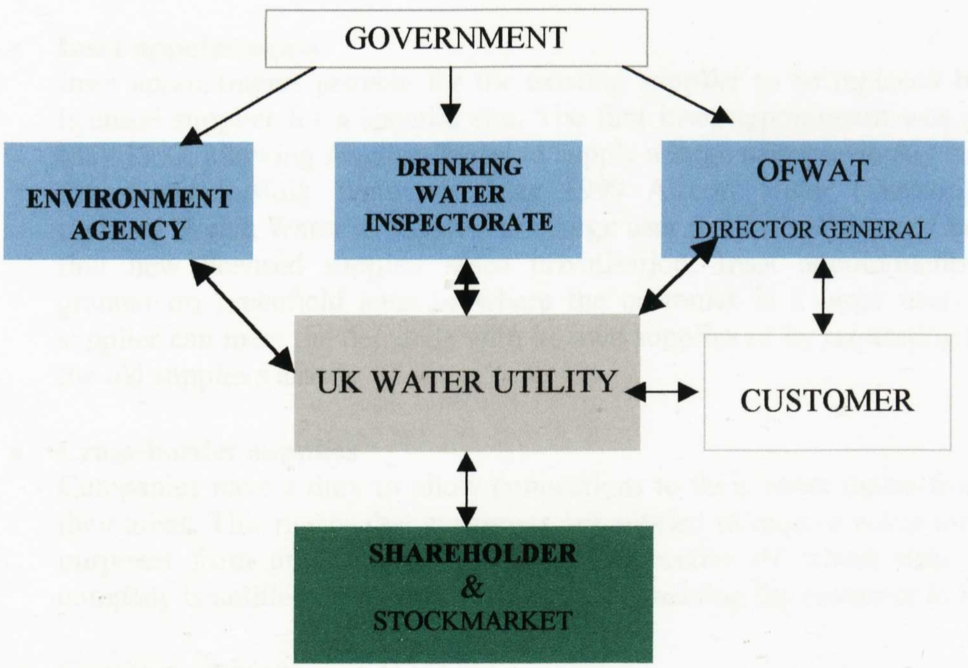

Figure 1.3 - UK Water Industry Stakeholders.

1.5.3 OFWAT

OFWAT, in particular the Director General of Water Services, is the government appointed economic regulator. His duties are outlined in Section 2 of the Water Industry Act 1991. The main function of the director general is to ensure that customers' interests are protected and that utilities' duties are carried out effectively and efficiently.

Customers' interests are protected by means of comparing levels of service between water companies.

Unlike other UK privatisation schemes, the companies were allowed to finance their operations and capital investment with an assured rate of return on capital. This was done to promote initial investment from shareholders. Prices were set on the basis of the capital investment that was required over a five year period to upgrade assets to meet current legislation and cover operational costs. This was negotiated between the company and the regulator and results in a "k" factor or the price increase which fixes the price limits for the next five years.

Companies can improve their profit margins by delivering the agreed targets in terms of treatment and levels of service at a reduced cost. Companies who do not, deliver programmes on time, meet efficiency targets or deliver required improvements in quality may be penalised in the subsequent review. Several utilities have been given interim adjustments of negative "K" factors as a means of instant penalty for incidents or continued levels of poor performance. This is a means to foster efficiency and competition in monopoly companies.

In addition, the Competition Act 1998 that came into effect from 1 March 2000 has set out to foster greater market competition by four means:

- **Inset appointments**
  Inset appointments provide for the existing supplier to be replaced by another licensed supplier for a specific site. The first inset appointment was granted in May 1997, allowing Anglian Water to supply a large user previously supplied by Essex and Suffolk Water. In May 1999 Albion Water (Shotton) Limited replaced Welsh Water as supplier to a large user in North Wales and became the first new licensed supplier since privatisation. Inset appointments may be granted on greenfield sites or where the customer is a large user. The new supplier can meet the demands with its own supplies of by requesting the use of the old suppliers assets.

- **Cross-border supplies**
  Companies have a duty to allow connections to their water mains from outside their areas. This means that customers are entitled to receive water for domestic purposes from any licensed supplier, irrespective of where they live. The company is entitled to recover the costs of connecting the customer to its mains.

- **Common carriage**
  Common carriage occurs when one service provider shares the use of another's assets, such as its pipe network or treatment works. The Competition Act 1998 opened up the barriers to entry in the industry by making it easier to

  1) Get a license for abstraction of water
  2) Negotiate a means to get the product to the customer.

If a company refuses a request for common carriage without proper justification it can find itself falling foul of the law.

- **Unregulated supplies**
  Private operators do exist and customers are entitled to buy water from them. They are currently not regulated and quality standards are intended to be enforced by local authorities, with the result that standards can often be poorly maintained. However the DWI does produce guidelines on point of use treatment systems.

These changes are significant as they may result in a greater diversity of water sources being combined in the distribution system and an increase in the number of sources being introduced into storage reservoirs

1.5.4 The Customer

The customer is entitled to compensation if their water supply is interrupted or in any way unfit for use. OFWAT and the DWI will investigate an incident on behalf of customers. Incidents also attract the attention of the media and can therefore have a direct and substantial impact on the share price and the value of the company. Increasing their susceptibility to hostile takeover.

Table 1.3 lists the number and nature of reportable incidents for 11 utilities, included in the DWI's 11th Annual Report to customers issued on the 11th July 2001.

Public prosecutions in 2000 resulted in direct costs of £50,000 for Utilities. An amendment of the K factor as a result of sustained lack of improvements in customer service, predominantly caused by iron and THM levels in distribution resulted in a fine of £25 million by OFWAT. A boil water notice issued as a result of disinfection failure or cryptosporidiosis incident at one of the larger UK utility treatment works is estimated to cost of the order of £8 million in customer compensation alone.

1.5.5 Future Legislation

The offence of corporate killing has yet to be created in the UK. As it was not included in this years Queen's speech, it is likely to only come into force before 2003. The current government's proposal is that if an employee or customer is injured or killed as a result of negligence on the part of a business, that company, and specifically those in charge are culpable (Running Scared, August 2001). With the recent announcement of the forthcoming public enquiry into the Camelford incident there is a significant risk that in the future individuals may be liable for criminal prosecution when water quality incidents result in detrimental affects to public health.

The management of the distribution system, in particular service reservoir performance may not be considered as great a risk in this regard as say a cryptosporidiosis outbreak. However service reservoirs are a key node in the distribution system and can have a significant effect on water quality as previously discussed. Therefore the implications in terms of public health and liability are not insignificant.

Utility	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Nature of Incident											
Supply of discoloured water	11	1	1	1	3		1	14	5	7	14
Wholesomeness concerns	4			1	4			3	1		2
Partial loss of disinfection	1										
Supply of water with taste and odour		1	1			1	1	1		3	
Failure of disinfection system			1							1	
Microbiological contamination			1				1		1		
Loss of supply					1		3			2	2
Contamination of source					1						
Boil water notice						2					
Failure of Treatment										1	
Cryptosporiosis in the community										2	
Formal Cautions			1		1					4	
Prosecutions*										2	

Table 1.3 - Drinking Water Inspectorate Reportable Incidents: July 2001

Several of the dirty water incidents and microbiological contamination incidents relate to service reservoirs

Prosecutions *

Section 70 of the Water Industry act makes it a criminal offence for a water company to supply water that is unfit for human consumption. The Inspectorate will prosecute if it believes that it has reliable evidence that water unfit for human consumption has been supplied, and that the Company does not have a defence that it took all reasonable steps and exercised due diligence to secure supply, and when such a prosecution is regarded as being in the public interest.

In October 2000, Utility 10 pleaded guilty to offences under Section 70 of the Water Industry Act 1991 of supplying water unfit for human consumption in April 1998. Three other cases were taken into consideration. The Company was fined a total of £12,000 with £10,471 costs. In all four incidents, discoloured water was supplied following work on the distribution system.
Also in October 2000, the Company pleaded guilty of supplying water unfit for human consumption. Two other cases were taken into consideration. The Company was fined a total of £20,000 with £7,100 costs. Contamination of water by hydrocarbons and diesel oil respectively occurred, and in the third case discoloured water was supplied.

2 Objectives

2.1 Business Case

The business case for improving water quality compliance is clear. The benefits of capital improvements at WTW can often be simple to evaluate in terms of percentage removal versus whole life costs.

Within the distribution system it can be difficult to assess the benefits in terms of water quality at the customer tap for substantial programmes of work. Many UK utilities have inherited distribution networks in excess of 30 years old, containing 100's of storage reservoirs the hydraulic performance of which are often poorly understood.

Without some understanding of the hydraulic performance of the individual reservoir, it can be difficult to assess what course of action is cost effective to reduce the risk of future quality failures. In these circumstances there is a tendency to implement then evaluate. This approach can lead to significant capital cost with limited accountable benefit.

With changing demographics and reduced leakage the nominal retention times in parts of distribution systems are increasing. The WRc guidelines on the operation of service reservoirs (Anon, 1993) recommend that the reservoir level is varied, to turn over the contents once every 48 hours to prevent stagnation. This can conflict with security of supply and pressure considerations and pose operational constraints and in any case does not assure complete water exchange.

In addition, pressure to reduce operational costs has resulted in the adoption of computer controlled pumping strategies that take advantage of reduced electricity tariff times (Brockton, 1987, Ormsbee, 1989). Currently decisions are being made which may take into account security of supply, but not the quality implications of pumping water into a reservoir at higher rates for reduced durations.

With increased competition and the introduction of additional sources into the network a fundamental understanding of the hydraulic performance of service reservoirs is required to ensure water quality is not compromised and operational flexibility can be maintained.

North West Water evaluated the "serviceability" of a reservoir on a scale of 1 to 5, see Table 2.1 below. Grade 5 having the worst performance. The structural condition of the reservoir was also taken into account. On this basis the capital programme for maintenance and remedial work was founded. Water quality compliance failures will raise the serviceability ranking.

Parameter	1	2	3	4	5
Chlorine Residual	Mean Value >=0.15mg/l S. Dev. <0.05	Mean Value >=0.15mg/l S. Dev >0.05	Mean Value >=0.12mg/l	Mean Value >=0.10mg/l	Mean Value >=0.10mg/l
Compliance Total Coliform	100%	100%	>=98%	>=95%	<95%
Compliance Faecal Coliform	100%	100%	100%	100%	<100%

Table 2.1 - Serviceability of Treated Water Reservoirs.

It was recognised that this method did not foster a pro-active approach to determining which reservoirs could be prone to future water quality non-compliance as a function of design and operation. A new method was required so that minor capital modifications could be undertaken cost effectively in line with the rolling five-year reservoir cleaning programme.

2.2 Objectives

The objectives of this body of work are therefore:

- To establish the hydraulic and mixing characteristics of the existing types of service reservoirs under different operational conditions.

- To evaluate how the hydraulic and mixing performance impacts upon water quality

- To recommend retrofit and operational changes to improve mixing characteristics. Retrofit solutions must be practically achievable and economically viable.

- To produce a business tool which will allow asset managers and operations to do a preliminary evaluation their own assets.

- To provide an aid to pro-active reservoir management decision-making.

- To provide a design document to ensure that future designs of service reservoirs take into account the hydraulic, mixing and quality implications.

Success will be measured in terms of practical application on full scale plant and adoption as a company standard.

The quality drivers for the programme are:

- achieve a reduction in the age of the oldest water, thereby reducing the potential for formation of disinfection by products.
- improved disinfection integrity and bacteriological compliance

- ensure disinfection integrity by the elimination of potential dead areas and future formation of dead zones within storage facilities
- reduce rapid variations in outflow water quality resulting from poor mixing
- highlight individual reservoirs which will be prone to deposition to enable the appropriate resources to be available during cleaning.

The operational drivers for the programmes are:

- reduce the requirement for changes in top water level - rapid volume changes, currently required to ensure periodic water replacement
- provide enhanced system process control
- ensure consistent hydraulic operation through the required range of operational conditions
- enable network modelling systems to accurately predict the water quality leaving a service reservoir
- reduce reservoir cleaning costs by reducing solids deposition

The business drivers for the programmes are:

- Clarification of the decision making process for remedial programmes as a result of water quality non-compliance
- Enable proactive process optimisation
- Ensure any capital programmes to enhance performance can be undertaken in line with reservoir cleaning programmes thereby reducing cost.

Layout of Thesis

Chapter 3 Previous Work
A review of previous work in the areas of tracer tests, reactor modelling, jet mixing, scaled hydraulic models and computational fluid dynamics.

Chapter 4 Methodology
This chapter outlines the reservoir survey conducted and the definition of the generic modelling programme. The experimental methods, model design and methods of analysis are presented.

Chapter 5 Results
The results of the generic modelling programmes are presented in order of geometry and aspect ratio.

Chapter 6 Discussion
Here the implications of the results in a hydraulic, water quality and business sense are discussed. The development of the service reservoir design guide is described.

Chapter 7 Conclusions and Further work
A summary of the most significant outcomes of the work is presented. Proposals for further work are also included.

3 Previous Studies

The issue of mixing in service reservoirs has been raised since the early 1980s. Many papers have discussed the issue of ensuring adequate mixing or uniform residence time for all flow passing through a reservoir. To compare the relative merits or approaches one must first establish a baseline of understanding for the evaluation tools, terms and models used.

3.1 Water quality monitoring

A utility survey conducted in the United States indicated that 53% of utilities that replied monitored chlorine free chlorine residual at service reservoirs with a frequency ranging from continuously to once per year (Kirmeyer (1999)). In the UK on line monitoring may be used on sites that are considered strategically important or have secondary chlorination. Otherwise weekly grab samples are taken at the same time as bacteriological samples.

Monitoring the quality of water entering and leaving the reservoir can provide information on the changes that are occurring as a function of storage. Burlingham (1995), however, determined that microbiological monitoring of a reservoir effluent did not give an indication of the extent of microbial colonisation in the biofilms and sediment within the reservoir. Boulos (1995) reported effective compartmentalisation of a reservoir in terms of high and low fluoride concentration. In general, reservoirs have not been designed with regard to ease of taking internal samples at spatially representative positions. Therefore such studies may give limited information of the internal quality of the whole reservoir.

3.2 Tracer Tests: Residence Time Distribution

In chemical engineering, to get the best performance from a vessel design a good basis is to match the fluid mechanics to the reaction kinetics (BHr Group (1995)). To achieve this one would generally ensure that the residence time corresponded to the required reaction time and the mixing rate corresponded to the reaction rate. As the traditional function of a service reservoir is to balance supply and demand and maintain pressure, a minimum retention time is not a pre-requisite. It is more important that the hydraulic performance does not result in water quality issues or higher operational costs (chlorine loss). The specific case where a service reservoir is to provide a dual disinfection (contact tank) will be discussed subsequently.

Levenspiel (1962) provides one of the most fundamental approaches to the use of residence time distribution analysis as a means of diagnosing non-ideal flow patterns in reactors, providing a basis for the comparison of the more complex models that have been applied to service reservoirs. The terminology used is widely adopted and has been adapted from Danckwerts (1953). The residence time distribution (RTD) or E curve, can be determined from injecting an inert tracer into the inlet of a closed vessel under steady state conditions and measuring concentration at the outlet over time. In general two types of trace injection are used, a pulse or (dirac delta function) and a step change. Other types of injection methods are discussed by Wen and Fan (1975).

The C Curve
With no tracer present, an instantaneous pulse of tracer is injected at the inlet. The normalised response is then termed the **C** curve. Normalisation is achieved by dividing the measured concentration C, by Q the area under the concentration time curve.

$$\int_0^\infty \mathrm{C}\,dt = \int_0^\infty \frac{\mathrm{C}}{Q}\,dt = 1 \qquad 2.01$$

Where

$$Q = \int_0^\infty \mathrm{C}\,dt \qquad 2.02$$

In a closed vessel for steady state flow the residence time for any batch of fluid entering the vessel will be the same as that leaving the vessel, hence the **C** curve is the exit age distribution (**E** curve) or residence time distribution curve (RTD).

The F curve
In this instance a step of tracer, concentration C_0 is injected with the inlet stream. The concentration C/C_0 is called the F curve. Where the relationship between the **E** and **F** curves for steady state conditions is given by equation 2.03.

$$\mathbf{F} = \int_0^t \mathrm{E}\,dt \qquad 2.03$$

The Mean and the Variance
Two important characteristics of the distribution are the mean of the distribution and the variance. For a C versus t curve, the mean is given by equation 2.04.

$$\bar{t} = \frac{\int_0^\infty t\mathrm{C}\,dt}{\int_0^\infty \mathrm{C}\,dt} \qquad 2.04$$

The variance represents the square of the spread of the distribution and has units of time^2 and is given by equation 2.05

$$\sigma^2 = \frac{\int_0^\infty \left(t - \bar{t}\right)^2 \mathrm{C}\,dt}{\int_0^\infty \mathrm{C}\,dt} \qquad 2.05$$

In evaluating models it is often commonplace to measure time in dimensionless time units. This then gives a dimensionless measure:

$$\theta = \frac{t}{\bar{t}} \qquad 2.06$$

3.3 Flow models

3.3.1 Ideal Flow

Two opposite ideal flow situations are described for steady state flow systems, plug flow and completely mixed flow.

Plug Flow

This is characterised by the fact that all the fluid elements entering the reactor will travel with the same velocity. No element of the fluid will mix with any element of the fluid ahead or behind. There may be radial mixing but no axial mixing along the flow path.

All elements of fluid entering the reactor will take the same time to pass through the reactor. In this instance the minimum retention time, to would be equal to the theoretical retention time, T.

$$T = V/Q \qquad 2.07$$

Where V is the filled volume of the reactor, and Q is the flowrate. Steady state conditions are assumed

Figure 3.1 shows an RTD curve for a perfect plug flow tank. For ideal plug flow, t_o/T would be equal to 1. In practice perfect plug flow is not achievable due to real fluid effects such as variations in velocity profile, axial dispersion and flow separation, therefore it is unlikely that t_o/T will ever exceed 0.7 for a well-designed plug flow tank (Crow et al (1997)). A useful parameter to gauge the degree of plug flow is the 'dispersion index'(t_{95}/t_{10}), which is the ratio of the times for 95% and 10% of the injected trace to pass through the reactor respectively. Other authors have defined the dispersion index or as t_{90}/t_{10}. The USEPA (1996) defined the dispersion index measured in these terms as 1 for a plug flow tank and 21.9 for a completely mixed tank. In practical applications however injected trace recovery in excess of 90% can be difficult to achieve.

Mixed Flow

This type of flow is described by many terms, perfectly mixed, ideal stirred tank or continuously stirred tank reactor (CSTR). It refers to mixing whereby as flow enters the tank, it is instantaneously mixed with the tank contents such that the exit stream has exactly the same composition as the fluid at any point within the reactor. The RTD curve shows that an initial value is reached at time t =0. Then an exponential decay occurs as the tracer is washed out of the reactor by the continuing inlet flow that contains no tracer, Figure 3.2.

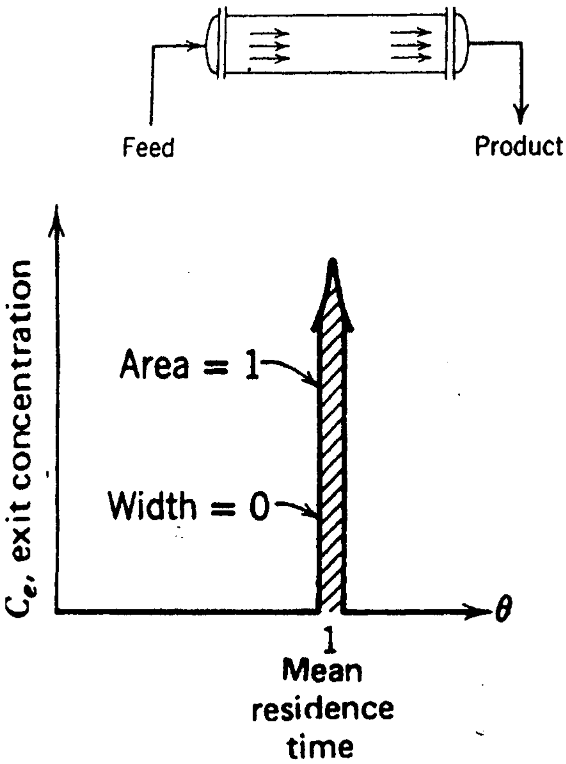

Figure 3.1 - Plug Flow

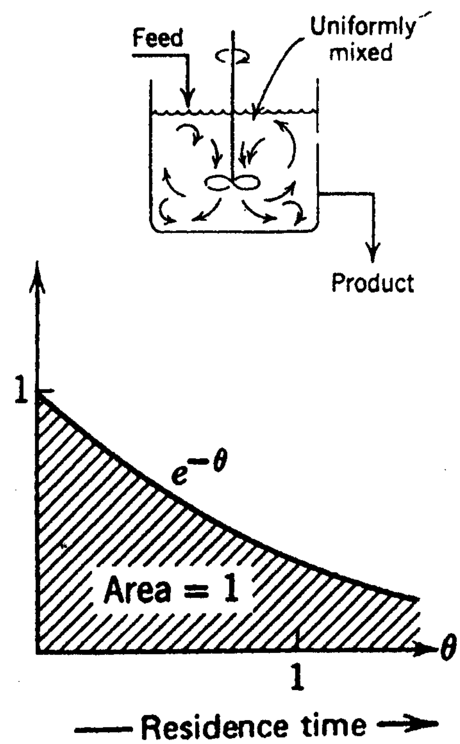

Figure 3.2 - Mixed flow

This is a simplified approach: real reservoirs or vessels never follow these two idealised flow patterns, plug flow or completely mixed flow. The deviation from the ideal models being a function of short-circuiting of fluid, fluid separation, formation of dead areas, recirculation, and boundary and temperature effects. They have, however, provided the basis for numerous more complex system models. Wolf and Resnick (1963) presented the application of **F** curves for a perfectly mixed tank.

3.3.2 Models for non –ideal flow

Many models are used to evaluate the deviation of real systems from plug flow or mixed flow ideals. Some are simple adaptations of the ideal cases while others consider the single reactor to be a complex series of ideal reactors in series and or parallel series.

Dispersed Plug Flow model

This considers the effect of back mixing and dispersion on the plug flow model. It assumes that there is no gross short-circuiting or dead areas within the tank. D the longitudinal or axial dispersion coefficient characterises the degree of back mixing. Where the vessel dispersion number is a dimensionless group, described by Levenspiel (1992) using equation 2.08. This is a measure the extent of axial dispersion.

$$\left(\frac{D}{uL}\right) \qquad 2.08$$

For negligible dispersion the dispersion number tends to zero, plug flow. For systems with large dispersion the dispersion number tends to infinity, mixed flow.

The dimensionless time C curves and variance curves are given by equations 2.09, 2.10 respectively (Levenspiel et al (1957)).

$$\sigma_\theta^2 = \frac{\sigma^2}{\bar{t}^2} = 2\left(\frac{D}{uL}\right) + 8\left(\frac{D}{uL}\right)^2 \qquad 2.09$$

$$C_\theta = \frac{1}{2\sqrt{\pi\theta\left(D/uL\right)}}\exp\left[\frac{(1-\theta)^2}{4\theta\left(D/uL\right)}\right] \qquad 2.10$$

For a single pulse tracer input Aris (1959) showed that this could be simplified to equation 2.11

$$\Delta\sigma_\theta^{\,2} = \frac{\Delta\sigma^2}{\bar{t}^2} = \frac{\sigma^2_{out} - \sigma^2_{in}}{\bar{t}^2} = 2\frac{D}{uL} \qquad 2.11$$

Where σ^2_{in} is the variance of the inlet pulse.

Hence analysis will allow variation of the tracer injection method to be eliminated.

The model has been used by Markse and Boyle (1973) to assess the hydraulic performance of contact tank facilities. Rhodes (1977) has also correlated the dispersion to disinfection efficacy. It is commonly used in the UK water industry as a means to assess the relative performance of chlorine contactors using lithium tracer tests. It has been applied as a means of evaluating modifications to the reactors to improve plug flow.

Mixed Tanks in Series Model

This model assumes that the reactor comprises of a number (N) perfectly mixed tanks in series. As N increases the RTD curve becomes increasingly symmetrical and approaches a Gaussian curve. Hence for N = 1 the C curve is a typical well mixed tank for N $= \infty$, plug flow. N can be estimated from the maximum the width at inflection and the variance. Where :

$$\Delta\sigma^2 = \sigma^2_{out} - \sigma^2_{in} = \frac{\bar{t}^2}{N} \qquad 2.12$$

Both of these models are commonly used in the evaluation of full-scale water and wastewater process plant.

Multiparameter Models

Multiparameter models are often used when single parameter models cannot account for the RTD curves observed. Again these are a means of putting the observed RTD data into a frame of reference to clarify or form a diagnosis of the flow pattern that is observed. Figure 3.3 depicts some of the models that may be used. Case studies of applications of multi parameter models are given by Goldstein (1972), Boulos (1994) and Mau (1995).

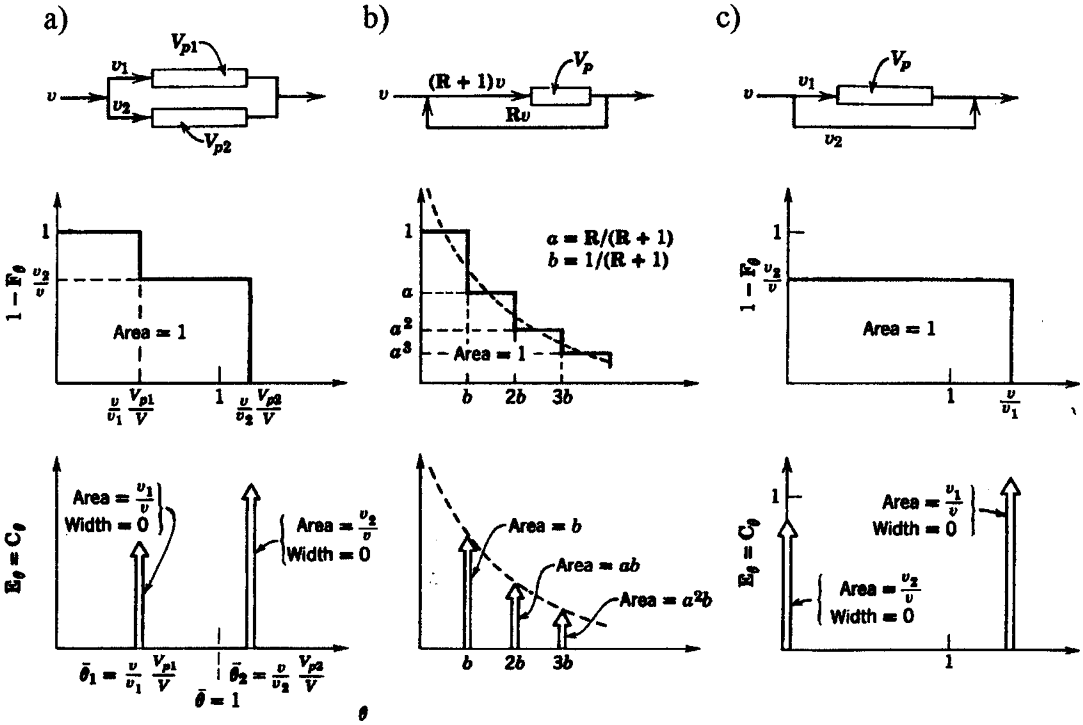

Figure 3.3 - Multiparameter Models -Levenspiel, O (1972)

One that has been widely applied involves the assumption that the system consists of a single vessel of which a certain volume is dead space (m) and the remainder is made up from plug flow (p) and completely mixed flow (1-p), Wolf (1963) and Rebhun and Argamon (1965), Antoniades (1982). This leads to the following form of the F curve equation

$$F(t) = 1 - e^{-\left(\frac{1}{(1-p)(1-m)}\right)\left(\frac{t}{T} - p(1-m)\right)} \qquad 2.13$$

Rearranging equation 2.13 and taking natural logarithms leads to equation 2.14

$$\ln[1 - F(t)] = \frac{-1}{(1-m)(1-p)}\left(\frac{t}{T}\right) - \frac{p}{(1-p)} \qquad 2.14$$

Hence a plot of ln (1-F(t)) against t/T will have a slope S given by

$$S = \frac{-1}{(1-p)(1-m)} \qquad 2.15$$

and an intercept I given by

$$I = \frac{p}{(1-p)} \qquad 2.16$$

To determine these values from the experimental the least squares line through the straightest portion of the curve is found. Thus in terms of the whole tank, m is a measure of the dead space, (1-m)p is a measure of the plug flow and (1-m)(1-p) is a measure of the mixed flow.

Antonaides (1982) used this approach to investigate the relative performance of contact tank inlet arrangement on a 1:7 scale model. Although the model aided him to arrive at a preferred inlet arrangement he noted that the errors were large. This is because the errors become significant at the extreme of the data. Brammer (1995) used the model to evaluate the performance of retrofit options to prevent short circuiting in flocculation basins. Oddie (1994), used the model successfully to assess the plug flow behaviour of a chlorine contactor. Rostron (1994) applied the model to a single chamber service reservoir reporting dead space (35%), plug like flow (0%) and mixed flow of 65%.

Boulos (1996) conducted internal sampling for fluoride and chlorine residual in an operational service reservoir. The results indicated that there was compartmentalisation of the reservoir such that there was a central core volume with lower fluoride residuals. Grayman et al (1996) went on to apply two types of system models to the reservoir: a simple mixed tanks in series model and a four-compartment model. The four-compartment model resulted in a better fit between the observed and simulated concentrations. However, he went on to comment upon the usefulness of compartmental and system models, emphasising that because the models do not profess to simulate the actual hydrodynamics of the reservoir, their veracity cannot be assured under conditions that differ significantly from those under which it has been defined and calibrated.

Distribution network models are widely used. Some deal exclusively with pressure headloss and flow data. Others attempt to predict water quality parameters. Rossman and Boules (1996) evaluated some of the numerical models available for modelling the transient behaviour of water quality in distribution. Two of the models were Eulerian - based upon the finite difference and discrete volume methods. The others were Lagrangian - time driven and event driven methods. Each method was encoded in an existing pipe system simulation and run on several pipe networks of different diameters. The results for all the methods were comparable in terms of accuracy but the different models were better at predicting different parameters, i.e. chemical transport, water age.

The majority of network models treat service reservoirs as pipe sections with a given 'nominal' retention time. They are assumed to exhibit near perfect plug flow and this is a source of some major discrepancies.

3.4 Plug Flow versus Mixed Flow for Storage Reservoirs

To clarify this one should return to the fundamentals of matching reaction time with residence time.

If a storage reservoir is to provide a contingency buffer of water and balance supply and demand then a minimum residence time is not required and excessive residence time is detrimental. Complete mixing is beneficial to reduce chlorine losses. The rate of disinfectant loss is concentration time dependant, (Fair (1948), White (1992). If a reservoir is well mixed the concentration within the tank is equivalent to the concentration leaving the tank. By contrast, in a plug flow tank the concentration at the inlet is higher, therefore the loss at the inlet will be greater and then decrease as the residual drops through the tank. Grayman et al (1999) showed that the difference in disinfectant loss between plug flow and mixed flow increased as a function of disinfectant reactivity, increased ratio of draw to fill time and decreased ratio of maximum to minimum water level.

If a reservoir is to provide a primary disinfection role, or qualify for a disinfection credit in the United States, then length of contact time with the disinfectant residual is critical. The contact time that is required and disinfectant concentration have already been discussed in depth in Chapter 1. To assure a minimum retention time and minimise the volume of the tank contact tanks are nominally designed as plug flow reactors.

The World Health Organisation recommends, using chlorine as a primary disinfectant a minimum CT of 15 mg.min/l. Which is equivalent to a free chlorine residual of 0.5mg/l for a period of 30 minutes at a pH less than 8, on condition that the turbidity is less than 1 NTU. In the UK each utility currently sets it own guideline targets on minimum contact time, which may be based upon measurement of t_o, t_5 or t_{10}.

In a study of the lithium tracer tests conducted on unbaffled contact tanks for one UK utility, t_o/T was measured as between 0.02 to 0.05. Therefore the plug flow was poor and the dispersion number high. However numerous studies have been conducted on optimising reactor design to achieve plug flow, including those of White (1986), Crow and Yeung (1997), Hannoun (1995), Crozes et al (1999) and BHr (1995). Guidelines for design are available in the literature. Tanks with plug flow efficiencies t_o/T of 0.7 have been reported to be attainable by simple retrofits of existing hydraulically poor tanks, Crow and Yeung (1997), Crozes et al (1999).

The selection of the most suitable flow regime for a given storage reservoir should be based upon primary function and number of alternative factors such as capital cost, operational cost, safety, performance stability and flexibility of operation.

It should be noted that the capital cost to retrofit to ensure good plug flow can be greater than ten times the capital requirement to achieve good mixing. This is based upon full-scale retrofit costing evaluations.

3.5 Mixing

Mixing rate is generally associated with faster kinetic reactions. In this instance one wants to ensure that stratification and dead areas do not occur and that rapid changes in the incoming water quality are not passed directly into supply. Changes in pH, dissolved oxygen and chlorine concentration can have an impact on the stability on biofilms in the distribution and customers are more acutely aware of changes in, rather than actual concentrations of individual parameters.

Mixing is achieved by a combination of macro and micro mixing. Macro mixing describes the breakdown of larger fluid elements into smaller elements, whereas micro mixing describes fine scale mixing within smaller fluid elements. For mixing in service reservoirs macro mixing will dominate.

3.5.1 Jet Mixing

A number of investigators including Johnston et al (1993), Ruochuan (1988) have assessed the use of jet mixing and pumped recirculation systems to achieve mixing and prevent stratification in raw and treated water reservoirs. Numerous comparisons of mixing and energy efficiency for aeration - bubble diffusers, pumped re-circulation and impeller systems have been made. Examples are given in the work of Wen (1988), Kortmann (1990) and Jirka (1991).

In jet mixing, fluid enters the body of the fluid as a jet whose diameter expands as it travels by entraining fluid. The replacement of the entrained flow creates a circulation. Hence the size and orientation of the inlet jet and the position of the outlet will affect the resulting flow pattern that is established. If we consider a vertical submerged inlet, the rising jet entrains flow, which is replaced by fluid re-circulating downwards. In this manner top to bottom re-circulation patterns can be established.

Stefen et al (1991,1992) conducted numerous studies upon the selective withdrawal and introduction of water jets at different positions and depths in a tank. These tests can be considered analogous to steady state operation of service reservoirs. Different inlet and outlet arrangements were used in reservoirs of various shapes. The effects of the model size, the reservoirs aspect ratio, jet orientation, jet momentum, multiple jets and Reynolds number were investigated. The work focused upon reducing stratification and a one-dimensional simulation model was applied to the experimental results obtained for vertical jets. Stefan reported that vertical jets were more efficient than horizontal jets for de-stratification and that 80% mixing was achieved when 20% of the water volume between withdrawal and re-injection points was recycled. Low momentum jets were determined to be more efficient than high momentum jets. Efficiency was measured in terms of energy demand to change in potential energy. In addition modelling predictions obtained with the Fluent CFD package were compared with experimental results.

Much of the current published work focuses on jets with high Reynolds number, Reynolds (1962) presented his own work and summarised that of others on low Reynolds number jets (<5000). McNaughton et al (1966) evaluated the effect of low Reynolds number jets in a vertical column using methylated blue dye as a visual tracer. The Reynolds number ranged from 100 to 28,000. It was determined that all sub turbulent jets have a lamina length a, where the flow is parallel sided and non-eddying. The effect of lamina length with inlet Reynolds number, Re_i for various tank and inlet sizes was evaluated. The four jet types observed were summarised as

- Dissipated Lamina — $Re_i < 300$
- Fully Lamina — $300 < Re_i < 1000$
- Semi-turbulent — $1000 < Re_i < 3000$
- Fully turbulent — $Re_i > 3000$

The exact Reynolds number range, for each condition, was influenced by the length of the tank. The end of the tank had the effect of inducing turbulence at a lower Reynolds number than was observed in a longer tank. It was concluded that the results obtained for a jet emerging into an infinite fluid would be different from those obtained for bounded jets. It was noted that very small differences in density between the tracer solution and the tank contents had a noticeable effect on the jet.

While jet mixing has been applied in a number of water and wastewater process applications (Guven (1983)). The problems associated with using jets are that depending upon their number and orientation they may create zone of very good mixing and also recirculation or dead areas. Jet mixing is reportedly used by at least one UK water utility to enhance mixing in service reservoirs. To date information on measured performance, operational power and maintenance costs has not been available. In this instance location of the jets will be critical in ensuring that dead areas are not established.

3.5.2 Tank mixing

The objective remains to achieve adequate mixing for sustained water quality at minimum operational and capital cost. The introduction of any mixing device within the reservoir presents an ongoing problem in terms of cost and maintenance. The most common and cost effective approach is to design the reservoir to utilise the momentum of the incoming flow alone. Many studies have evaluated the optimum placement and sizing of the inlet pipe to achieve the best mixing characteristics The WRc recommendations on service reservoir operation prepared by Anon (1993), reported that inlets were generally situated diagonally opposite the outlet or adjacent to it. The type of inlet was generally an upturned bellmouth above TWL or a horizontal straight pipe located just above the bottom of the tank. In some instances the outlet acted as the inlet where a common shared main was used- these were termed push- pull tanks.

Reitinger (1983) suggested that the optimum type of inlet was a horizontal straight pipe located below the lowest operating top water level. He suggested that inlets of other types such as the upturned bellmouth contributed little towards mixing and hence regions of slow moving water would develop.

Coanda effect

When a jet discharges close to a wall or solid boundary, it entrains the surrounding fluid. A low pressure region is created between the jet and the boundary such that this side of the jet adheres to the boundary. This is called the Coanda effect and is described by Jirka (1991). Grayman (1999), gives the conditions proposed for attachment, as equation 2.17.

$$F_r > 5.3\frac{h}{d} \qquad 2.17$$

Where

F_r = Froude Number
h = perpendicular distance between the jet and the wall
d = inlet diameter

3.5.3 Mixing Time

Empirical and mathematical models that predict the time required to mix the incoming flow with the contents of the tank have been derived and compared over the years by a number of investigators including, Fosset and Prosser (1949), Fox and Gex (1956), Van de Vusse (1959), Okita and Oyama (1963), Fosset (1973), Simpson (1975), Germeles (1975), Hoffman (1992), Rossman (1997) and Grayman (1999).

Okita (1963) and Rossman (1997) both evaluated mixing time in cylindrical tanks, during a fill cycle. Okita (1963) evaluated mixing in cylindrical tanks of 0.4 and 1m. The tanks were filled with tap water and the inlet nozzle situated at the base of the tank angled between 0 to 90°. Mixing time was defined as the time elapsed between injection of the tracer and when no concentration difference was evident in the tank.

The Rossman's (1997) experimental set up was similar, this time a step impulse was used. A 1.2m diameter tank was initially filled with de-ionised water, the inlet flow was tap water. A series of 6 conductivity probes were mounted in the vessel and the inlet flow temperature and tank contents temperature where monitored. Rossman (1997) used this experimental set up to evaluate mixing performance and the effects of momentum and buoyancy forces on mixing. Each experiment was considered complete when the tank contents had reached a mixed or stratified condition. Mixing was determined by initially smoothing the time series conductivities, pair averaging then comparing the relative range of conductivities for each time period. The mixing formulas derived are summarised in table 3.1 below.

Author	Formula	Constant	Notes
Fosset & Prosser	$\frac{KD^2}{M^{1/2}}$	K=8	D= tank diameter M= Inlet momentum
Van de Vusse	$\frac{KD^2}{M^{1/2}}$	K=9	
Okita & Oyama	$\frac{KH^{1/2}D^{3/2}}{M^{1/2}}$	K=4.6	H = Water level Re > 5000
Fox & Gex	$\frac{KH^{1/2}D^2}{Re^{1/6}M^{2/3}g^{1/6}}$	Dependant on units	Re= Reynolds number G=gravitational constant

Table 3.1 - Mixing time models

Stratification

Following the work of Rossman (1997), Grayman et al (1999), went on to define the limiting conditions for stratification with positive and negatively buoyant vertical jets in bounded conditions as:

$$F_d > 1.5\frac{H}{d} \qquad 2.18$$

For positively buoyant inflow, inlet flow at higher temperature than tank contents

$$F_d > 0.8\frac{H}{d} \qquad 2.19$$

For negatively buoyant inflow, inlet flow at lower temperature than tank contents

Where F_d is the densimetric Froude number defined as:

$$F_d = \frac{U}{(g^1 d)^{1/2}} \qquad 2.20$$

U	= inlet velocity
d	= inlet diameter
H	= tank depth
g^1	$= g(\rho_i - \rho_t)\ \rho_t$
g	= acceleration due to gravity
ρ_i	= inlet flow density
ρ_t	= initial tank flow density

Coefficient of Variation

Coefficient of Variation (CV) is a statistical measure of mixture quality that is becoming increasingly used in the water and chemical industries to evaluate reactor mixing and the performance of mixing devices. It is defined as the standard deviation of concentration measurements divided by the mean concentration as shown in equation 2.21

$$CV = \frac{\sqrt{\left[\sum_{i=1}^{n}\left(Ci - \bar{C}\right)^2\right] \Big/ (n-1)}}{\bar{C}} \tag{2.21}$$

As such the change in CV over time when measured at fixed points will provide an indication of the rate of mixing that is being achieved. A CV of 0.05 indicates that 95% mixing has been achieved.

Generally step tests are used with multiple arrays of sampling points distributed across the cross sectional area in the case of a pipe or channel or within the reactor. The number of samples taken and the points of sampling will obviously influence the statistical significance of the results.

3.6 Hydrodynamic models

The advantage of hydrodynamic models is that one can establish the physical boundaries of the model, ie: tank shape, depth, operating criteria etc and as one is dealing with fundamentals, the performance of the model can be evaluated independently with no requirement for calibrating field data. So that a design may be tested and modifications made and corresponding water quality conditions simulated before the full scale plant is built.

3.6.1 Physical modelling studies

Physical scaled models are often constructed to simulate tanks and reservoirs of all manner of configurations, Simpson (1975), Germeles (1975), Yalin (1971), Hammer (1986), Grayman (1995).

These type of models rely upon the ratio of the forces in the model being equivalent to the ratio of the forces within the full scale plant or similitude. The model is therefore used to determine the hydrodynamic behaviour of the full scale system. For a given system the predominant forces need to be identified and the scaling laws for these between the model and full scale plant derived. For single-phase flows used in the water industry the reactors are geometrically similar and the ratio of the scaling laws for the flows are typically Reynolds or Froude scaling as described by Rouse (1946).

Dyes are generally used for a rapid evaluation of the bulk hydrodynamics. Other inert tracers such as salt, lithium, fluoride or rodamine are used with on line measurement at the outlet or potential grab samples to determine the RTD. Where possible, model simulations are compared with full scale plant data to verify the model predictions.

In 1970, Langer presented a paper that showed the flow pattern in a number of rectangular reservoirs for steady state operation. The results indicated that significant dead areas could form leading to increasing water age. A number of the geometries show the typical flow separation that one might expect at inlets and after baffles. One arrangement presented showed a square tank with an inlet parallel to the side wall in one corner and an outlet in an adjacent corner. The resulting flow pattern was a peripheral circulation with a large central quiescent zone.

Grayman reported a similar flow pattern in 1999. However, he reported no significant dead areas and good mixing when the tank was in fill only mode. Intermittent dye tests were also conducted which showed that mixing within the tank still continued after the inlet flow ceased. Pillars were included in the model, these were reported to have an impact on the resulting flow pattern but not the mixing time. General recommendations are given on the sensitivity of the mixing on placement of the inlet for square, rectangular and circular tank. However, no significant dead areas are reported. It is notable that the position of the outlet is not given. It is inferred that all of the tests were conducted in fill mode. Hammer and Marotz (1986), Baur and Eisenbart (1982) and Poggenburg (1981) did not report significant dead areas in their respective reservoir studies.

Teefy (1997) conducted an extensive physical modelling study in 1993, to evaluate potential retrofit options to the San Jose Water treatment plant reservoir to enhance disinfection credit. The reservoir was a circular 27m diameter tank with a maximum operational depth of 4.8m with a common 30 inch diameter inlet/outlet pipe. Flow through the tank during normal operation could not be assured and hence no disinfection credit could be claimed. Froude scaling was used and a 1:15 scale model built. More than 50 configurations were tested although only a limited number of results were reported. The objective of the modelling programme was to maximise t_{10} and achieve a minimal t_{10} of 20 minutes. Based upon the modelling the optimum design to promote longer t_{10} retention times was considered to be a tangential inlet, discharging parallel to the side wall, with the outlet pipe extending to the centre of the tank. This promoted a spiral type flow pattern around the periphery of the tank, into the central outlet. After installation at full scale the arrangement was tested using receding mode fluoride step tests. Fluoride was normally dosed upstream of the reservoir, each test was started by terminating the fluoride feed. Taking grab samples and analysing with ion selective electrodes then determined fluoride concentrations at the outlet. The pertinent results are summarised in table below.

Flowrate M3/s	Reservoir Level m	T min	t_{10} measured full scale	t_{10} predicted model	t_{10}/T measured full scale	t_{10}/T predicted model
0.25	2.4	116	27	33	0.23	0.28
0.25	3.0	144	32	31	0.22	0.21
0.25	3.6	173	45	23	0.26	0.13

Table 3.2 - Teefy et al (1997): Modelling versus full scale results

Significant variation was noted between the model predictions and full-scale results, the model predicted that minimum retention time notably decreased with increasing tank depth and theoretical retention time. The opposite trend was observed on the full scale. The frequency of grab samples is also not given so it is difficult to determine whether errors were incurred during the full scale plant trials as a function of method.

Grayman et al (1996) conducted a series of similar circular model tests based upon the Ed Heck reservoir in Azusa, California. Again Froude scale modelling was used. Initially two small-scale models were built with length scales of 1:160 and 1:80 resulting in models of diameter 300 and 600mm respectively. Experiments on these models were abandoned as it was reported that diffusion of the dye in the water made it difficult to follow the advancement of the flow. No further details are reported however when one scales the other critical parameters as shown in Table 3.3, it is evident that the operational depths and flowrates were very small under these conditions the frictional effects in the models are likely to have been significant. The full-scale diameter to depth ratio was 5.1:1 and tank diameter to inlet diameter ratio was 76:1.

Scale	Full scale Diameter D M	Inlet Diameter d m	Tank Depth h m	Inlet Flow l/s	Inlet Velocity m/s
prototype	46.90	0.610	9.14	526.16	1.80
Model 160:1	0.29	0.0038	0.057	0.001625	1.425 E-01
Model 80:1	0.59	0.01	0.11	0.01	0.20

Table 3.3 - Grayman et al (1996): Model Scaling

A further model with scale 42:1 was built and potential retrofits to improve the performance were trialed. A similar geometry to that described by Teefy et al, was evaluated, which incorporated a central low-level outlet. The test results for this geometry are summarised in table below. In this instance this was not considered to be the most effective geometry.

Tank Diameter m	Inlet Diameter m	Tank Depth h	Inlet Flow l/s	Velocity m/s	T min	t_0 min	t_{circ} min	t_o/T	t_{circ}/T
1.12	0.01	0.17	0.03	0.18	89.70	9	4	0.10034	0.044595

Table 3.4 - Grayman et al (1996): Circular tank results

The studies above are conducted for a similar geometry and depict similar results although they cannot be directly compared. In both instances the focus of the work was to increase the minimum contact time.

CBI Walker Incorporated, manufacture a circular contact tank which utilises this design, termed the Ribbon Flow™ Clearwell (1995). The company's marketing literature reports that the ribbon flow achieves a "superior baffling factor" without the use of extensive baffles and also suggests that the design consistently achieves t10 / T greater than 0.7, which is significantly greater than that reported by Teefy et al (1997).

Yeung et al (1997) applied a similar concept as a retrofit to two distinct complex rectangular reservoirs with multiple inlets. The existing design resulted in erratic chlorine residuals and chlorine loss. Upon full scale plant implementation, stable chlorine residuals are being achieved irrespective of the mode of operation of the reservoir(s).

3.6.2 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics programs are used in a wide range of chemical and process engineering applications, including aeronautic design, combustion, power generation etc. The basic program capabilities include 2D/3D geometries in Cartesian, cylindrical or general curvilinear co-ordinates, steady state or transient flow, incompressible or compressible flow, conduction convection, mixing of chemical species including multi-component diffusion models, laminar flow of non-Newtonian fluids.

In the past CFD programs for complex or large systems could only be run on very large computers typically only found at Universities or research institutes. However with advances in computer architecture and code the technology is becoming more widely and economically available.

CFD packages modelling is based upon solving the conservation equations for mass, momentum, energy and chemical species using a finite volume difference method. The development of the body fitted co-ordinate system (BFC), Thompson, 1974, allowed these methods to be applied to more intricate geometries. Once the computational grid has been set up the boundary conditions in terms of inflow and outflow are established. The equations are then solved across the grid until the solutions converge. As many of the applications deal with turbulent flow a turbulence model is required with a wide range of applicability. The k-ϵ model defined by Rodi (1980) is applicable to a wide range of flows. Wang et al (1998) successfully used it to simulate the flow separation that occurred around baffles in contact tanks.

When considering whether or not a CFD simulation is appropriate, one will need to take into the account the complexity and size of the tank to be modelled (i.e.: steady state, transient state, multiple inlets, large volume), as these factors will have a significant impact on the simulation time.

Grayman et al (1999) developed a finite element tool called Hydro tank that was specifically designed for non-expert use on modelling storage reservoir. A comparison was presented between the Hydro tank simulation and an alternative CFD package simulation for a discrete case study.

Rowe and Hutchins (1995) used CFX FlOW3D, to simulate water age and chlorine distribution in a rectangular service reservoir. Davis (1993) used the same package in a study of an Olympic swimming pool, the objective of the study was to reduce the impact of relatively high velocity inlet to attain a uniform low velocity.

Morrison (1999) conducted a series of modelling studies on rectangular tanks using the commercial finite volumes code CFX4.1. Average water age was established using a scalar transport equation. Initially a CFD simulation was compared with the result of a physical modelling simulation. There were marked differences in the resulting RTD's produced. However both simulations predicted a strong peripheral circulation and central quiescent area. Morrison went on to evaluate and present flow visualisation plots, RTD curves and water age plots for rectangular service reservoirs with aspect ratios of 1.1, 1.5:1 and 2:1 for three inlet types, an annular and circular inlet above TWL, and a horizontal circular inlet at base level.

Xongfu et al (1993) modelled an annular contact tank using CFDS FLOW3D, The tank consisted of a circular tanks with an inner circular baffle wall. The tank had an outer and inner wall diameter of 12.97 and 7.63m respectively. The volume of the tank was $300m^3$ with a typical flow of 9.5 Ml/d. The inlet was 400mm in diameter and located near the base of the tank, the outlet an overflow weir. The simulation showed that the minimum retention time was 12 minutes, with 25% of the trace exiting the tank in under 30 minutes and the tank efficiency t_o/T of 27%. Modification of the inlet only to produce a uniform flow distribution resulted in an increase in to 29 minutes and a corresponding increase in t_o/T to 64%.

Brocard and Vandeventer evaluated the design of the North Royalton storage tank in Cleveland, using FLUENT. The design is similar to that evaluate by Xongfu et al (1993). In this instance the circular tank consisted of a inner and outer ring which were modelled separately. The full scale plant had a diameter of 32m and operational depth of 6m.The inner and outer sections had volumes of 12,300 m3 and 7532m3 respectively. The outer ring showed good plug flow characteristics as might be expected t_{10}/T =0.6. Spiral baffling was evaluated for both tank section, and the direction of rotation from inner to outer tank and outer to inner were considered. Spiralling outwards had slightly better performance, with t_{10}/T of 0.80 predicted for the inner tank and t_{10}/T of 0.89 for the outer tank. These results indicated a better plug flow performance than previously predicted in modelling studies by Hannoun (1998) for circular tanks.

Tuan Ta (1997 & 1998) conducted a series of modelling studies of treated water reservoirs, which showed that there is a strong tendency for short-circuiting and stagnation as a result of horizontal flow circulation in large shallow reservoirs. From the results of a number of reservoir simulations he concluded that the location and geometry of the inlet were important factors determining the flow pattern in the tank. Having the inlet on a side wall generated horizontal flow circulations, these recirculation patterns resulted in stagnation region and short circuiting. Directing the inlet upwards or downwards could be used to avoid horizontal flow circulation and internal baffles and columns encourage directional flow.

4 Methodology

4.1 Programme

North West Water has more than 400 operational service reservoirs in distribution. The majority of previous studies in the literature had focussed on individual reservoirs. It was apparent that it would not be prudent to model each reservoir individually and therefore a generic approach would be required. An initial survey of all of the reservoirs was conducted to establish basic reservoir shapes and aspect ratios. It became apparent that reservoirs could be loosely generically grouped in terms of general shape, i.e. square, rectangular, circular. Each was individual with respect to its exact geometry. At this juncture operational boundaries had not been established.

The complexity of the programme needed to be refined and reduced. As water quality compliance was a key business driver for the research, it was considered prudent to ensure that the study included reservoirs with associated water quality compliance issues. A further in depth survey of 166 reservoirs was conducted. The water quality compliance figures for North West Waters 400 service reservoirs were compiled for the previous 5 years. Reservoirs that were associated with water quality problems including bacteriological, THM's, erratic chlorine residuals, high iron levels, dirty water incidents or tastes and odour complaints were prioritised. Reservoirs with a poor serviceability score and a selection of reservoirs where secondary chlorination had been installed were also included. The remainder were selected randomly. The reservoir survey document is included in Appendix D.

Of the 166 surveyed, sufficient information upon which to base modelling criteria was only established for 133. The detailed survey revealed that the majority of NWW's reservoirs could be divided into groups on the basis of shape and geometrical aspect ratio. Prior CFD and physical modelling studies had shown that tanks with similar aspect ratios and inlet and outlet arrangements exhibited similar flow characteristics. So the reservoirs were initially divided into discrete groups based upon similarity of shape and aspect ratio, Table 4.1.

	Numbers	**% of completed surveys**
No of sites included in survey	166	
Groups		
Rectangular		
Aspect ratio 1:1 to 1:1.5	71	53.4
Aspect ratio 1.5:1 to 2.25:1	25	18.8
Aspect ratio 2.25:1 to 3.3:1	9	6.8
Aspect ratio 3.3:1 to 5:1	0	0
Circular: Single and Twin compartment	23	17.2
Other	5	3.8
Total	133	
Insufficient information	33	

Table 4.1 - Summary of survey information.

Of the tanks surveyed 54% were single compartment, 40% were twin compartment with reported full height dividing walls and 6 % twin compartment tanks with mid height dividing walls.

This formed the basis for the study. Within each grouping there was still a vast range of individual geometries and operational conditions. To evaluate each with a site specific model would not have been feasible. Hence generic evaluations and solutions were sought to ensure that the full-scale optimisation programme could be fast and the resulting benefits rapidly returned to the business.

For each grouping, the reservoirs that fell into this category were segmented in terms of inlet and outlet type, number and relative position. It was apparent that a number of inlet and outlet arrangements were commonplace. Each discrete arrangement was given a "series" label. This formed the basis of the generic evaluation programme. Series which related to multiple tanks were prioritised.

The operating range for each series was established from data provided in the survey information. This obviously resulted in what would have been a very wide range of tests. North West Water had compiled a typical demand curve for design of service reservoirs, based upon the typical mode of operation for the majority of their reservoirs. See Figure 4.1.

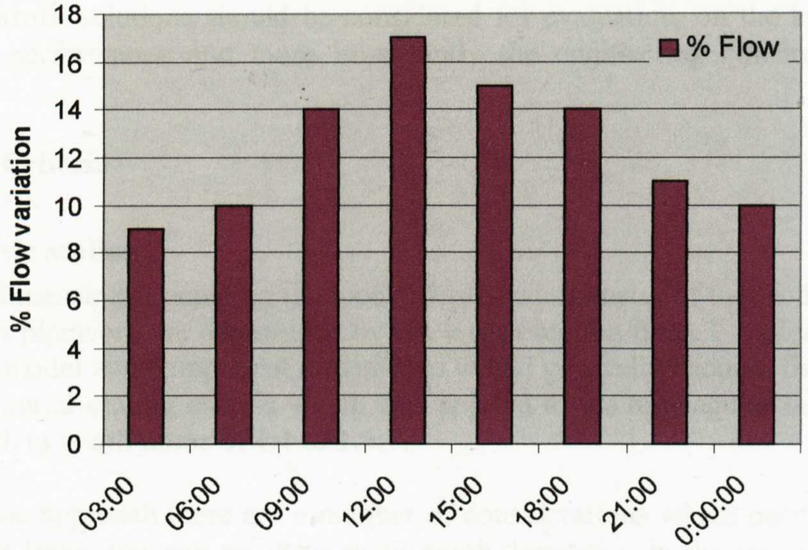

Figure 4.1 - Typical reservoir demand profile.

This showed that many of the reservoirs would have some degree of constant draw, the night time flow being determined predominantly by industrial use and leakage. The majority of the reservoirs surveyed did not fall into a fill then draw mode of operation, the only tanks that fell into this category as a function of design were the push pull tanks.

The frequency, volume and duration of inflow was very variable, from continuous flow to short pumping durations once per day to the extremes of uncontrolled unknown inflow. It was therefore determined that the evaluation for each series would need to include

i) Steady state tests: Equivalent inflow and outflow and constant level.
ii) Transient tests: variations in inflow and outflow, changes in level
iii) Intermittent flow: Fill then draw

In addition some form of flow visualisation aid would be required. The experiments would need to provide a baseline for direct comparison with other series within the generic group and any retrofit options. Retrofit options were also given discrete series labels.

4.2 Physical Modelling

Physical modelling was chosen as the most appropriate means to conduct the evaluations. It was chosen in preference to CFD for a number of reasons.

The computer time required to conducted CFD simulations with intermittent flow and transient tests were considered to be prohibitive. The number of generic groupings and individual tests series that would need to be conducted would have required 100% access to computer time. It was considered unlikely that a programme of the scope outlined could be completed by an individual within the time period. The sponsoring utility did not have internal CFD capability so all modelling work to have had to be conducted at the University, where access to computer time could not be assured.

A key factor was ensuring that the sponsoring company had "ownership" of the results to ensure that recommendations were implemented at full scale. Having a modelling facility at a major WTW site ensured that asset managers and operations were present when modelling tests were conducted that were relevant to their assets. All concerned parties participated fully in discussions to determine what potential retrofit solutions should be considered for evaluation, on the basis of potential for improvement in performance and more importantly the engineering constraints and economic viability.

4.3 Scaling Criteria

4.3.1 Geometric scaling

All basic length dimensions, including the model depth and diameter of the model components such as inlet and outlet pipework are determined by the length scaling ratio, L. After the length scale is chosen all of the model and component dimensions would generally become fixed. Table 4.2 is an extract from the initial scaling criteria which was applied to the rectangular full scale tanks in the survey with length to width ratios of 1:1 to 1.5:1.

In taking this basic approach there are a number of considerations which need to be made. If the scaling ratio, L is large, this can result in small depth dimension in the model. The effect of this might be that too much of the depth (y) may be taken up by the boundary layer, potentially resulting in misleading results.

A method frequently used in river modelling can be adopted in these cases, where a distorted vertical scale is used. Increasing the vertical scale without changing the horizontal scale will exaggerate the model depth. This would require an increase in velocity to maintain Froude number similarity, discussed subsequently. The main danger with this approach is that it assumes that any flow pattern in the model is two dimensional in the horizontal plane. For individual models this would require confirmation. In addition if internal features in the model such as supporting structures, benching are scaled geometrically they can result in extensive frictional losses in the model, which again can lead to misrepresentation.

		Prototype Data		Model Data				Model Flowrates	
Site Number	Reservoir <u>Length</u>	Ratio Length Width	Inlet 1 : Flowrate	Model Length	Scale L	Model Minimum Depth	Inlet diameter	Reynolds no. scaling	Froude no. scaling
	m		Ml/d	M		Mm	mm	l/s	L/s
50	34.5	1.44	10.0	3.41	10.1	61	30.2	9.65	0.36
49	34.5	1.44	10.0	3.41	10.1	61	30.2	9.65	0.36
47	73.0	1.30	3.5	3.41	21.4	26	14.3	1.60	0.02
139	109.0	1.21	3.3	3.41	31.9	18	9.6	1.01	0.01
125	48.4	1.00	30.0	3.41	14.2	32	75.3	20.63	0.46
134	12.0	1.00	1.0	3.41	3.5	114	43.4	2.77	0.50
71	44.2	1.11	7.5	3.41	12.9	55	29.5	5.65	0.14
72	44.2	1.11	12.5	3.41	12.9	55	29.5	9.41	0.24
86	16.0	1.42	1.3	3.41	4.7	77	42.7	2.70	0.32
51	30.2	1.00	7.5	3.41	8.8	71	50.9	8.27	0.37
84	47.5	1.10	21.0	3.41	13.9	51	21.9	14.72	0.34
41	123.0	1.35	40.0	3.41	36.0	19	33.9	10.83	0.06
35	10.0	1.00	0.1	3.41	2.9	137	52.1	0.33	0.08
65	7.6	1.44	0.5	3.41	2.2	135	45.6	1.97	0.70
45	10.0	1.11	1.3	3.41	2.9	128	0.0	0.00	0.98
99	9.0	1.24	0.1	3.41	2.6	118	38.8	0.30	0.08
46	20.0	1.11	9.0	3.41	5.9	77	52.1	14.98	1.26
73	17.4	1.00	2.6	3.41	5.1	75	35.0	4.98	0.52
96	21.6	1.33	0.2	3.41	6.3	59	12.7	0.31	0.02
85	47.5	1.10	26.0	3.41	13.9	51	21.9	18.22	0.42
24	21.6	1.00	0.1	3.41	6.3	47	32.2	0.14	0.01
166	46.9	1.09	20.0	3.41	13.7	44	51.0	14.18	0.33
118	40.0	1.14	2.8	3.41	11.7	32	13.0	2.33	0.07
88	90.0	1.32	45.0	3.41	26.3	30	26.0	16.64	0.15
115	54.0	1.45	1.5	3.41	15.8	28	24.1	0.92	0.02

Table 4.2 - Scaling criteria

4.3.2 Flow scaling

Froude number scaling

The majority of physical modelling studies reported in the literature use Froude number scaling. Froude number (Fr) similarity is maintained between the model and the full scale, see equation 4.1 below.

$$Fr = \frac{U}{\sqrt{gd}} \qquad 4.01$$

Where

U = inlet velocity

d = inlet diameter

g = acceleration due to gravity

As the flow in a reservoir is slow moving and not generally subject to significant gravity related flow effects, strict adherence to Froude scaling should not be a pre-requisite.

In some instances either due to selected scaling criteria or selection of model components, the frictional forces at the model surface can be dominant and result in significant boundary layer effects. Under these conditions the momentum of the inlet flow at Froude scale can be insufficient to overcome the frictional forces in the model, resulting in misleading results. A practice that has been used to overcome these effects is increasing the flow scaling using multiples of Froude number. This approach has been adopted by a number of investigators (Yeung H, 1996,1997). The advantage of this approach is that the time taken to run the tests and the volume of water that is used are significantly reduced and frictional effects can be minimised. Table 4.2 gives some initial scaling criteria applied to a number of the full scale reservoirs with length to width ratios 1:1 to 1.5:1. It is apparent that for some of the reservoirs the Froude number scaled inlet flowrate at these geometric scaling ratios would be very small (~ 0.01 l/s) and difficult to control and accurately sustain. The scaling relationships for models based upon Froude and multiples of Froude number are given in Table 4.3.

Parameter	Froude number	Multiples of Froude number
Length scale	L	L
Area scale	L^2	L^2
Volume	L^3	L^3
Flow scale Q	$L^{5/2}$	$nL^{5/2}$
Time scale	$L^{1/2}$	$1/n\ L^{1/2}$

Table 4.3 - Scaling criteria for Froude and multiples of Froude number.

Reynolds number scaling

Reynolds number similarity can also be used to scale the flow see equation 4.02.

$$\mathrm{Re} = \frac{\rho U d}{\mu} \qquad 4.02$$

Where

ρ = fluid density

μ = fluid kinematic viscosity

For the reservoirs surveyed the inlet Reynolds number was typically greater than 100,000. To maintain similitude under these conditions the model inlet flowrates and resulting velocities would have been excessive as shown in Table 4.2. Reynolds number scaling was therefore considered inappropriate in this instances as the high inlet flows would result in excessive surface disturbance and unrealistic flow effects.

If each site were to be modelled individually many of the inlet flowrates required for Froude number similitude would be small. It was considered likely that modelling at Froude scale in these instances would result in exaggerated boundary layer effects in the model. Conversely the flowrates required for Reynolds number similitude were excessive and considered likely to result in unrealistic surface waves in the model. Hence it was rationalised that a multiple Froude scale approach may be required. This was validated during the initial test series which are subsequently discussed.

4.4 The modelling facility

4.4.1 Model sizing and design

During previous studies separate models were constructed for different tank types. This was considered impractical given the cost of fabrication of separate models and the range of the generic programme. It did not permit the impact of minor changes in aspect ratio to be evaluated.

Therefore a single adaptable physical modelling facility was determined to be more appropriate. One of the physical limitation of adapting models during experimentation appeared to be the increased potential for leakage when a model was altered. Hence it was determined that the modelling facility should facilitate rapid changes in geometry, aspect ratio and inlet and outlet size and position.

The maximum physical size of the modelling facility was based upon the results of the survey information. An iterative approach was taken to determine the maximum base size. The survey information was compiled in a basic spreadsheet and various geometric scaling ratios applied to determine suitable length and width criteria for the model base with corresponding model inlet and outlet pipework diameters, as shown in Table 4.2. Important factors in the determination of the final size included:

- Ensuring scaling resulted in suitable and available model inlet / outlet pipework diameters, ie: ½, 1 , 1 ½ inch .
- Ensuring scaling resulted in suitable model operational depths of between 100 to 550 mm.

Previous studies had shown that it was important to maintain a minimum operational depth in the model otherwise frictional affects across the model base, side walls and any internal structures could become exaggerated in the model. The smaller the operational depth the more significant boundary effects were likely to become.

The maximum operational depth was chosen with regard to the mass of the water volume and the requirement for potential strengthening of model side panels and the structural strength of the model base and support. It was important for the base of the model to be at a suitable height to facilitate model modification and three-dimensional viewing during flow visualisation tests.

In addition the volume of water required to undertake basic tests was a consideration. The larger the physical size of the model the greater the volume of suitable water would be required. It was initially assumed that a minimum of four times the model volume would be required for simple steady state tests

After numerous iterations the final base of the model was 6000 mm by 4500 mm. It was manufactured from 10 mm thick galvanised steel plates. Supported by a network of 35 supporting legs at 1000 mm centres.

The steel base was covered in a sectioned PVC floor. The base of the floor was covered with a network of drilled and tapped holes with helicoil screw threads of maximum depth of 18 mm. These were strategically placed to facilitate rapid model adaptation without the requirement to drill additional holes. When not in use each hole could be plugged such that it was flush with the adjacent PVC floor. Thereby reducing any additional base level frictional effect. Figure 4.2 is an engineering drawing showing the position of pre drilled holes and depicting the experimental set up for the largest model plan area.

The model walls were constructed from sections of 600 mm high, 12 mm thick clear Perspex with 20 mm flanges. The use of various lengths enabled easy modification of rectangular tank aspect ratios and sizes. Pre-fabricated corner, circular and internal wall sections were also specified and provided. All of the modelling components were fabricated from smooth materials to minimise surface frictional effects. The modelling and model components were supplied by Model Products, Bedfordshire, UK.

4.4.2 Data Collection and Logging

The model control, data collection, conditioning and logging was all undertaken in a programme written in LABVIEW version 5 provided by National Instruments. The system allows the user to build a series of virtual instruments and controls. Such that all aspects of the modelling facility could be monitored and controlled by a user interface on the computer screen. See Figure 4.3.

The control philosophy had to be defined and written and numerous iterations of the software and plumbing have been required to ensure flow and level control. Detailed schematics of the control logic and control system hardware are given in Appendix A.

The final control programme enabled automated multiple inlet / outlet flowrate and tank level control, conductivity measurement for twelve conductivity probes with associated thermocouples for temperature compensation, inlet flow conductivity control system with associated P&ID control and automatic data logging of all variables to the control PLC. The model control and logging system used the SCX1-1000 mainframe and required one SCX1-1300 board and two SCX1-1325 boards

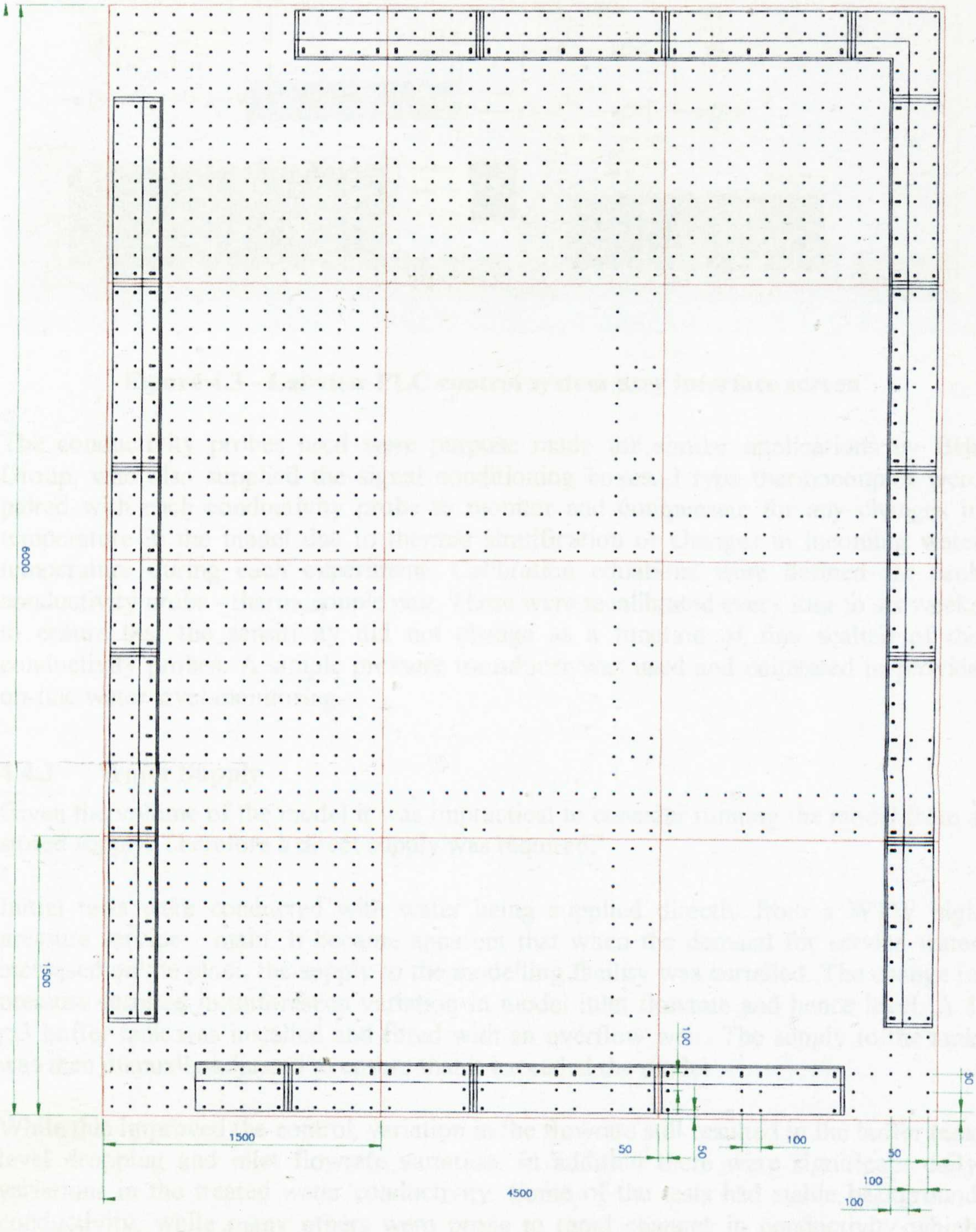

Figure 4.2 - Model Plan drawing showing position of drill and plug holes.

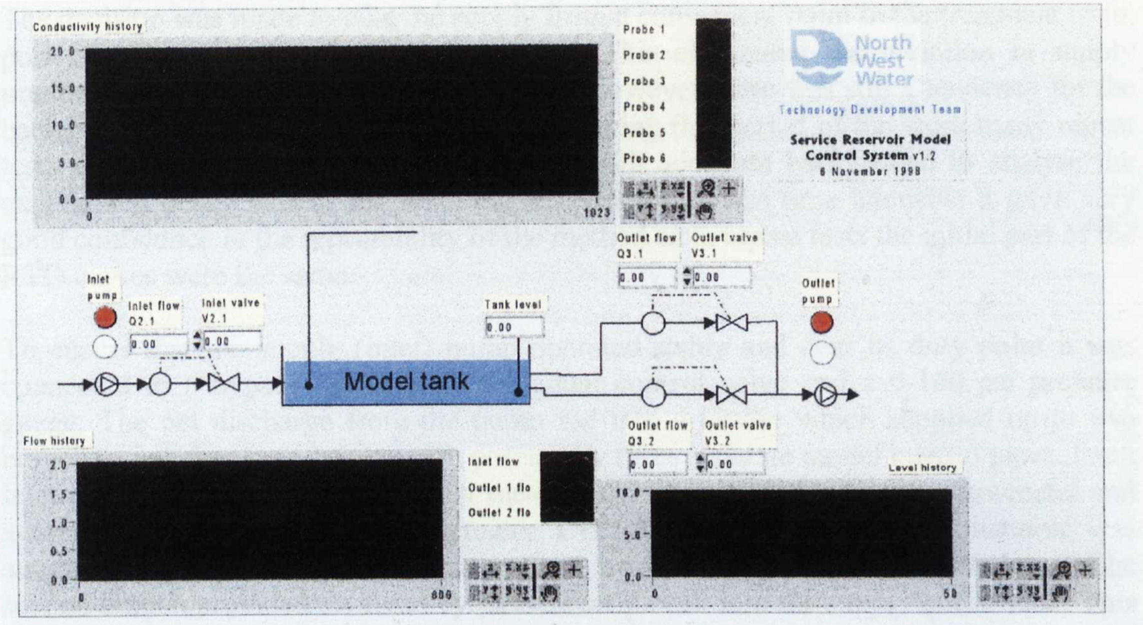

Figure 4.3 - Labview PLC control system user interface screen

The conductivity probes used were purpose made for similar applications by BHr Group, who also supplied the signal conditioning boxes. J type thermocouples were paired with each conductivity probe to monitor and compensate for any changes in temperature in the model due to thermal stratification or changes in incoming water temperature during each experiment. Calibration equations were defined for each conductivity probe - thermocouple pair. These were recalibrated every four to six weeks to ensure that the sensitivity did not change as a function of fine scaling of the conductivity probes. A simple pressure transducer was used and calibrated to provide on-line water level monitoring.

4.4.3 Water Supply

Given the volume of the model it was impractical to consider running the model from a stored supply. Therefore a direct supply was required.

Initial tests were conducted with water being supplied directly from a WTW high pressure service main. It became apparent that when the demand for service water increased on the plant, the supply to the modelling facility was curtailed. The change in pressure resulted in unforeseen variation in model inlet flowrate and hence level. A 1 m3 buffer tank was installed and fitted with an overflow weir. The supply to the tank was then manually adjusted to ensure that it exceeded the model

While this improved the control, variation in the flowrate still resulted in the buffer tank level dropping and inlet flowrate variation. In addition there were significant daily variations in the treated water conductivity. Some of the tests had stable background conductivity, while many others were prone to rapid changes in conductivity which made analysis problematic.

The decision was made to take the supply from a convenient point in the treatment train, post filtration and pre final pH correction. This eliminated the variation in supply pressure and reduced conductivity variation. However there was still a tendency for the background conductivity to drift over time. During this period of the work many repeat tests were conducted to attain a single test with adequate background to analyse the exponential decay part of the RTD curve. Whilst this was time intensive it gave very good confidence in the repeatability of the method as in repeat tests the initial part of the RTD curves were the same.

To ensure that the supply (inlet) pump operated stably and near its duty point it was connected to a bypass circuit with a manual control valve and a 0-100 psi pressure gauge. The net discharge from the pump fed into a header which supplied up to two branches, one feeding a header with potentially three separate model inlet(s) pipes. Each inlet pipe flow could be individually metered using an ABB Magmaster flowmeter and automatically controlled via an Actuator TYPEA20 valve. The valve adjustment was automatically controlled to provide a fixed or variable flowrate via Labview. The second branch provided a valved by pass directly back into the supply buffer tank. This meant that the pump basically operated with constant supply and discharge flow and pressure. This system minimised variation in the model inlet flow considerably. Typically the flow variation during any steady state tests was maintained within +/- 2% of the set point value. Once optimised changes in flowrate could then be simply and accurately selected on the Labview virtual instrument panel and the actuated valves would open or close to attain the new setpoint. This eliminated time intensive manual adjustment of control valves.

The supply and discharge pumps were selected were C0350/07 Lowara pumps, which had a capacity of 5 l/s at approximately 6 to 10 m head. The four manual isolation valves required were Crane DISIA valves.

Having achieved stable and controllable inlet flowrates in this manner a similar system was used for the outlet pump control. In this instance the suction to the pump was fed from a header with potentially three separate model outlet pipes. Two of the outlet pipes could be individually metered using ABB Magmaster flowmeter and automatically controlled via an Actuator TYPEA20 valve. The valve adjustment was automatically controlled to provide a fixed or variable flowrate via Labview. The outlet flow from the model was discharged to sewer.

4.4.4 Inlet water quality control

Full residence time distribution curves are required for in depth analysis of the each test and to ensure comparative results. The tail end of the exponential curve provides the most significant source of information for tanks with poor hydraulic performance. So it was essential to be able to measure the tail end of the curve above any background noise. Data analysis can become very complex if the background levels are variable. In some instances incoming background variation or noise level can be much greater than the signal that one is trying to identify and quantify, leading to more complex analysis and uncertainties in results.

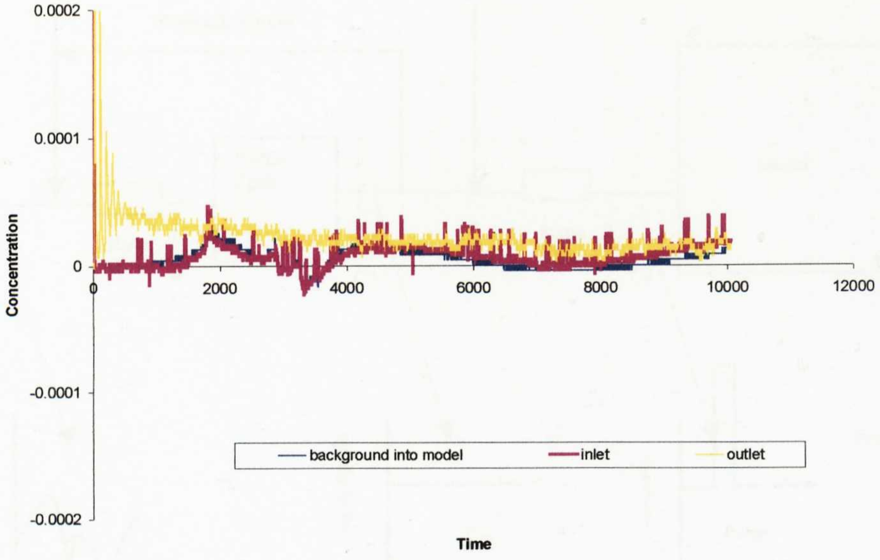

Figure 4.4 - Series 1 trace showing poor background conductivity

A number of solutions were proposed to overcome this:

i) Monitor the conductivity of the flow into the model and adjust the output trace accordingly for variations in the incoming conductivity. This is difficult and prone to large experimental errors, especially when the behaviour of the reservoir is largely unknown.

ii) Provide a buffer tank of well mixed water. For the transient tests the estimated size of the buffer storage was considered excessive, in excess of 40 m^3 as tests would have to be run overnight. There were also concerns about temperature fluctuations in the buffer tank effecting the results.

iii) Correct the conductivity of the water coming into the model up to a specified level, prior to pulse / step addition, by means of injection of a weak salt solution.

Solution iii) was the approach that was adopted. A mixed buffer tank was also included before the model to reduce any additional fluctuations. The control system was adapted to accommodate a well-controlled background level and a step change which could be maintained and a pulse, dirac-delta function, which was delivered via manual injection.

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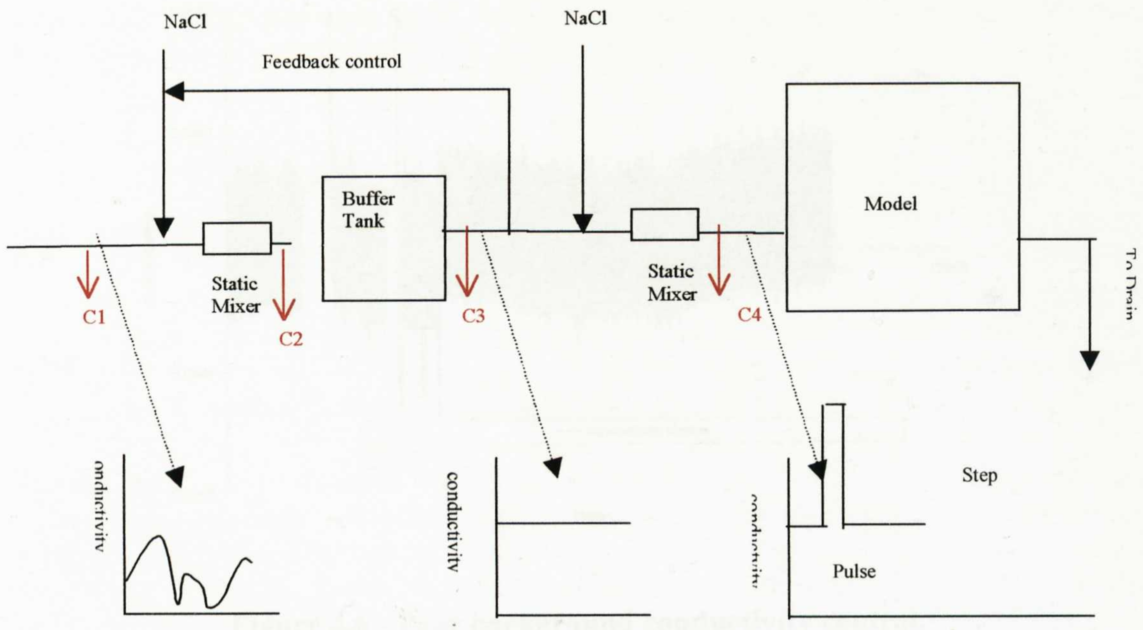


Figure 4.5 - Schematic of conductivity control system

The incoming conductivity was measured at a point C1, then a fixed concentration of salt solution was injected prior to a static mixer using a Watson and Marlow peristaltic pump. The on line measurement of conductivity at C1 , C2 and C4 formed the basis for the feedback control algorithm. A schematic of the control system is shown in Figure 4.5.

The initial performance of the control was poor, Figure 4.6. After a series of modifications including temperature correcting each conductivity probe, the addition of pulsation dampers and systematically altering the concentration of salt solution, the background conductivity control improved by two orders of magnitude. The response of the PID controller was then modelled and tuned using the Ultimate Cycle Method. This measures the system response to given incoming stimuli and allows the PID parameters to be calculated from the system ultimate gain (G_u) and the ultimate period (P_u). Once optimised this resulted in robust background conductivity control.

The final injected salt control solution strength was .005 mol/l. Laboratory grade sodium chloride was used. In addition to the conductivity control and outlet conductivity probes, eight further conductivity probes were positioned in a matrix within the model itself.

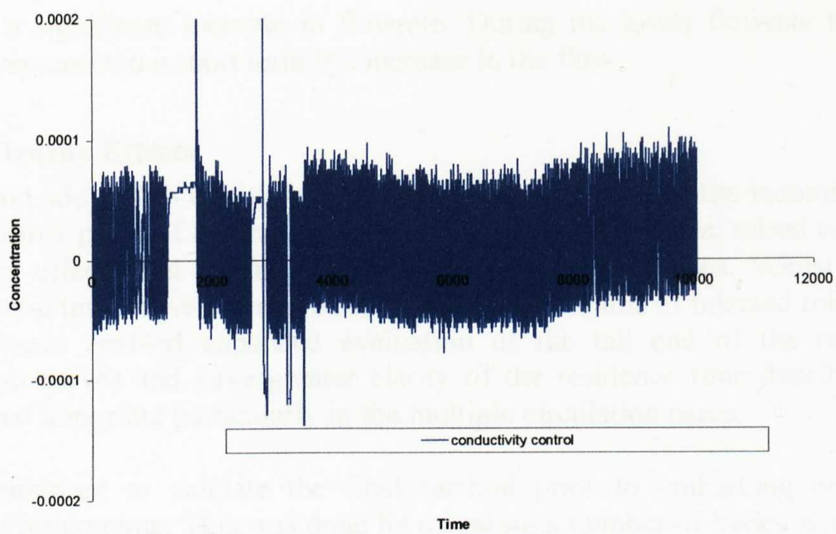


Figure 4.6 - Poor background conductivity control.

4.4.5 Tracer Injection system

The tracer that was used to generate all the steady state and transient test RTD curves was laboratory grade sodium chloride. Sodium chloride was chosen as the trace as it facilitated online monitoring and allowed results to be analysed as they were generated. Diluted dyes were used for flow visualisation tests.

The same injection technique was used for both the dye and salt tracers. This comprised of a valved T pipe section off the main inlet pipe(s) with a sealed plastic plug through which a hypodermic needle was inserted into the main flow. The tracer was injected directly into the main inlet flow and then the hypodermic needle withdrawn and the valve closed. The trace was then mixed with the main body of the inlet flow via a static mixer. The T section was minimised as far as possible to prevent backmixing in the pipe. A conductivity probe was inserted in the inlet pipe to monitor the exact nature and shape of the inlet pulse, ensuring that poor injection techniques or potential backmixing of the inlet trace within inlet pipework did not bias the resulting residence time distribution curves obtained from the outlet conductivity probes.

The inlet probes also provided a second point of reference for the background conductivity of the water entering the model. Consideration was given to automating the injection system. Several designs were considered but rejected due to complexity and the time requirement for further optimisation. The ability to monitor the nature of the inlet pulse allowed for any minor variation in the injection technique to be taken into account in the subsequent analysis.

The salt trace concentration was 5.5 mol/l and the trace volume was varied from 5 to 200 ml depending upon the individual test inlet flowrate. The trace was injected typically over a 5 second period such that injected trace was typically less than 5% of the inlet flow. This was important because one did not want the injection technique to represent a significant increase in flowrate. During the lower flowrate tests the trace injection represented a short term 9% increase in the flow.

4.4.6 Density Effects

The method adopted to elevate and control the conductivity of the incoming flow, then inject a further pulse of higher molarity salt solution as the trace, raised concerns about the density effects that this might induce in the resulting traces. Whilst the resulting concentration time curves were similar using 5 and 200 mls of injected trace. The larger volume traces enabled enhanced evaluation of the tail end of the residence time distribution curves and gave greater clarity of the residence time distribution curves. This proved important particularly in the multiple circulation cases.

It was important to validate the final method prior to embarking on the generic modelling programme. This was done by repeating a number of Series steady state tests without background conductivity control using lithium chloride as the tracer. There was no lithium present in the supplied water and it may be accurately detected in the laboratory at concentrations of 5 μg/l. Therefore Lithium presented an ideal trace which could be used in minute concentrations thereby minimising any density effects due to tracer concentration.

The resulting RTD curves were then compared to those obtained using the corrected background and salt tracer technique.

Figure 4.7 shows one of the comparative results for the same steady state test conditions with the same inlet and outlet configuration. Inlet and outlet flowrate of 0.9 l/s +/- .02 with an average model depths of 259 and 252 mm for the salt and lithium tests respectively.

These results and the other comparative studies indicated that the background conductivity correction and tracer injection method did not appear to be inducing significant density effects which would compromise the flow pattern and resulting RTD curves obtained during a test. On repeat tests dye was also injected with the salt trace to visually check for density effects.

Nominally all flow visualisation tests were conducted at the end of a steady state test such that the flow visualisation results could be directly correlated with the RTD data obtained. In addition the conductivity of the dye would not interfere with the trace.

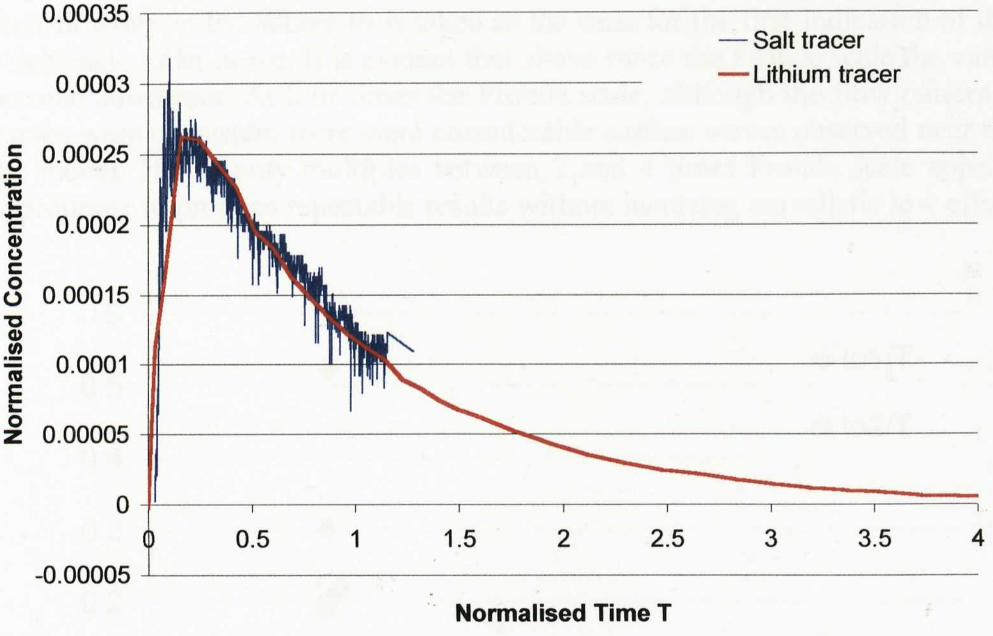


Figure 4.7 - Comparison of salt and lithium trace techniques to evaluate tracer density effects

4.5 Validation of experimental conditions (or Preliminary Tests)

The technique of using multiple Froude number flow scaling had been used during previous studies on contact tank performance. During these studies modelling results had compared favourably with full scale lithium chloride tracer tests. It was therefore important to establish whether similar scaling criteria could be applied during the reservoir studies. An in depth study of one of NWW's more strategic and largest reservoirs was conducted as part of the modelling facility commissioning process. The reservoir was of irregular shape with a novel inlet arrangement and two distinct outlets. Details are given in Appendix C. Due to the size of the full scale plant the geometric scaling ratio of the physical model was 68.3:1. Using the nominal depth of the full scale reservoir as a starting point this resulted in an operational depth in the model of approximately 85mm.

The inlet flowrate was initially set at Froude scale (0.13 l/s) and steady state tests conducted. At these flow rates the inlet flow became completely dispersed. Repeat tracer tests under steady state conditions resulted in different results. During flow visualisation tests it was difficult to determine any dominant flow pattern. Dye was injected at the base of the model and it was evident that the boundary layer at the base of the tank was approximately 25 mm. Hence the boundary layer occupied a significant percentage of the model volume.

The tests were repeated increasing the inlet – outlet flowrates in multiples of the Froude scale. At twice Froude scale a distinct flow pattern was observed, which was repeatable at three and four times Froude scale. The RTD curves were comparable. Figure 4.8

below shows the values of t_0 /T for outlet 1 and outlet 2 respectively plotted against the inlet flowrate in l/s. Where to is taken as the time for the first indication of the trace to reach each outlet probe. It is evident that above twice the Froude scale the value of t_{01}/T became consistent. At four times the Froude scale, although the flow pattern and RTD curves were consistent there were considerable surface waves observed near the inlet of the model. Hence only multiples between 2 and 4 times Froude scale appeared to be appropriate to produce repeatable results without incurring unrealistic low effects.

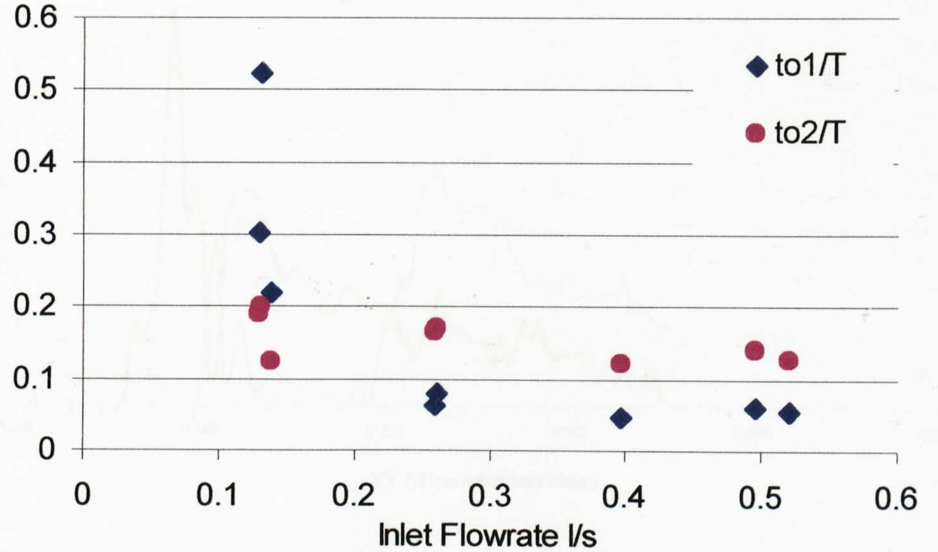


Figure 4.8 - Variation of to_1/T and to_2/T with Froude scaled flowrate

Using this scaling criteria the performance of the model was established under a wide range of operational conditions and a range of retrofit solutions trialed. It was evident that a complete change in flow pattern occurred in the model when operated with the same steady state inlet and outlet conditions but different depths. While the results were generally supported by operational rhetoric. There was a concern that what was being observed was not a real flow effect but possibly a function of exaggerated frictional effects in the model due to small operational depth.

To provide confidence that the flow effects were real, increased vertical plane modelling was conducted. The oblique wall (see Appendix C) and the inlet wall were constructed to contain water depths scaled of 34:1. The 1:3 sloping benching and the steps and the inlet baffle wall were also modelled at this distorted scale. The results obtained with the increased vertical plane scaling concurred with the original results. Transients in the flow pattern were established under comparable conditions. However they were not as pronounced during the increased vertical scale tests. A synopsis of the results is given in Appendix C.

During this period a lithium tracer test was conducted on the full scale reservoir. The operational staff attempted to maintain steady state conditions over the several days required for the test. However as inlet and outlet(s) flowrates were not metered it was not possible to ascertain the exact operational conditions during the full scale tests. Figures 4.9 and 4.10 below allows comparison of the lithium tracer tests with steady state tracer test 4, which was conducted at comparable depth. Details of the experimental conditions are given in Appendix C. It was evident that the generalised shapes of the RTD curves for outlets 1 and 2 were very similar. This gave confidence that the flow effects observed in the model at shallow depths and increased Froude scale were real.

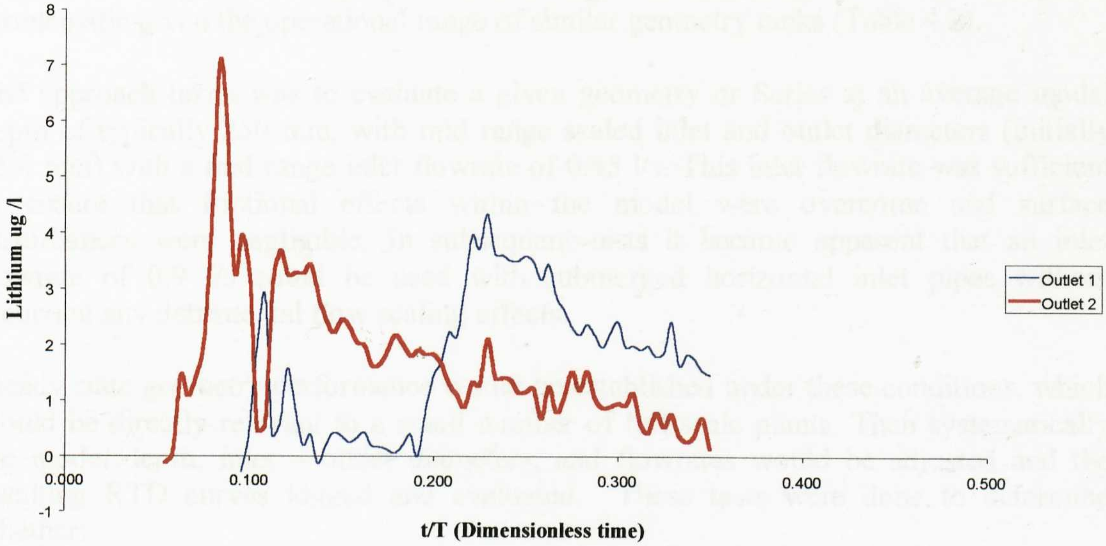


Figure 4.9 - Full-scale Lithium chloride tracer tests

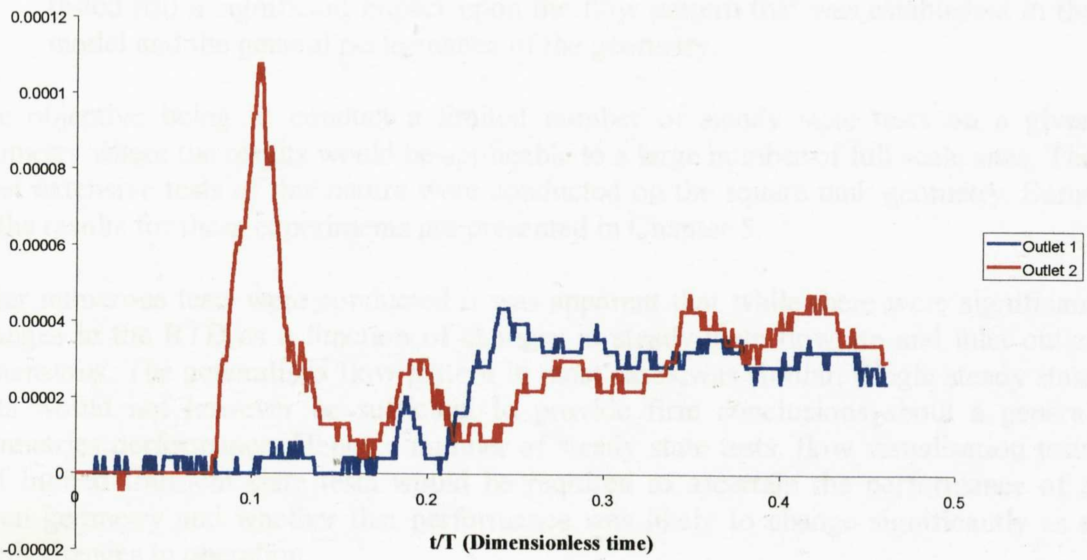


Figure 4.10 - Steady state model tracer test 4

4.6 Test methodology for generic study

4.6.1 Steady state tests

The initial tests and previous studies had established that modelling at multiples of Froude scale was a reasonable approach given that unrealistic surface effects could be avoided. In the generic study selection of a single Froude scaled flow would have been problematic given the operational range of similar geometry tanks (Table 4.2).

The approach taken was to evaluate a given geometry or Series at an average model depth of typically 250 mm, with mid range scaled inlet and outlet diameters (initially 25.4 mm) with a mid range inlet flowrate of 0.45 l/s. This inlet flowrate was sufficient to ensure that frictional effects within the model were overcome and surface disturbances were negligible. In subsequent tests it became apparent that an inlet flowrate of 0.9 l/s could be used with submerged horizontal inlet pipes without incurring any detrimental flow scaling effects.

Steady state geometry performance would be established under these conditions, which would be directly relevant to a small number of full-scale plants. Then systematically the model depth, inlet – outlet diameters, and flowrates would be adjusted and the resulting RTD curves logged and evaluated. These tests were done to determine whether:

- Experimental results were repeatable
- Changes in the scaling ratios applied for a given geometry produced different results.
- Changes in inlet (outlet) diameter to tank width or depth ratios and flowrates tested had a significant impact upon the flow pattern that was established in the model and the general performance of the geometry.

The objective being to conduct a limited number of steady state tests on a given geometry where the results would be applicable to a large number of full scale sites. The most extensive tests of this nature were conducted on the square tank geometry. Some of the results for these experiments are presented in Chapter 5.

After numerous tests were conducted it was apparent that while there were significant changes in the RTD as a function of changes in steady state flowrate and inlet outlet dimensions. The generalised flow pattern in most cases was similar. Single steady state tests would not however be sufficient to provide firm conclusions about a general geometries performance. Hence a number of steady state tests, flow visualisation tests and limited transient state tests would be required to ascertain the performance of a given geometry and whether that performance was likely to change significantly as a result changes in operation.

The initial steady state tests conditions for each generic model group are given in Table 4.4. The RTD curves presented in Chapter 5 are representative of these modelling conditions unless otherwise stated.

Shape and aspect ratio	Model dimensions (mm)	Inlet / outlet diameters (mm)	Inlet – Outlet Flowrate (l/s)	Model Depth (mm)
Rectangular				
1.0:1	3418 x 3418	12.7 to 50.8	0.12 to 0.9	200 to 350
1.4:1	3418 x 2418	25.4	0.45 to 0.9	200 to 270
1.78:1	3418 x 1918	25.4	0.3 to 0.9	250 to 270
2.3:1	3418 x 3418	25.4	0.9	250 to 270
2.8:1	4418 x 1918	25.4	0.45 to 0.9	250 to 270
3.9:1	2418 x 618	12.7	0.45 to 0.9	200 to 400
Circular				
	2600 diameter	12.7 to 25.4	0.45 to 0.9	200 to 370

Table 4.4 – Range of initial steady state test parameters

Schematics for the model system for each generic group of tests are given in Appendix B.

4.6.2 Intermittent flow tests

The intermittent flow tests were conducted in the same way for each series. The inlet flowrate was selected for the individual test typically 0.9 l/s for submerged inlets and 0.45 l/s for high level inlets. The initial model operating depth was selected. These two factors determined the initial model retention time T. The inlet flow was then introduced for a period of T/2, at which time the inlet flow was terminated and the outlet was operated at the same fixed flowrate for a period further period of T/2. In all cases the model had been operated under steady state conditions for time period T prior to the injection of the tracer pulse, which was introduced with the inlet flow. The intermittent flow tests were conducted to evaluate potential changes as a result of having inlet or outlet flow only.
The transient tests would be used to evaluate the potential for performance change under changing flow and level conditions

Schematics of the model set up and internal tank process positions for each series of tests are given in Appendix B.

4.7 Data Logging and analysis

All of the flow, level, conductivity and thermocouple data were stored in a time series format in the Labview program. When the run was terminated the data was automatically stored on the hard drive of the PLC in spreadsheet format. This could then be readily transferred onto any other computer for further analysis. The Labview programme completed a series of tasks in loops; one loop included the storage of data. Hence data was not downloaded at exact 1-second internals, in some instances it took more computer time to complete as series of tasks. As the time was constantly logged this did not present any problems in analysis.

4.7.1 RTD analysis

Normalised concentration and time curves were used to compare the shape of residence time distribution curves. Dimensionless time measurements such as t_o/T, t_{10}/T dispersion index and circulation times t_n/T were used in conjunction with the general shape of the RTD curves, as a baseline for direct comparison of series, individual results and verify experimental methods and reproducibility.

The RTD curves were also used to establish the degree of internal recirculation in the models; these were correlated with the results of the flow visualisation tests and the work of previous authors.

Short-circuiting is referred to in the design guide document (appendix D) and was measured as the volume of the injected trace that leaves the tank in the first peak of the RTD curves. Where the RTD comprised a single major peak only, followed by exponential decay then this was not considered to be short-circuiting.

4.7.2 Water exchange

An accepted form of presenting the steady state test results is the **F** curve as defined in section 3.2. To obtain this from the concentration time curve requires normalisation as previously discussed. The presentation of F curves assumes that all of the injected trace has been recovered.

Throughout the initial trials of the generic modelling study it became apparent that achieving 100 % trace recovery was rare. even though the experiments were run for durations in excess of 5 T. It was evident that this was partly a function of experimental errors but more significantly determined by the hydraulic performance of the particular geometry under test.

Geometries that resulted in significant dead areas, as evident during the flow visualisation tests, resulted in correspondingly poor trace recovery. In these instances analysis of the internal tank conductivity probes showed that poor recovery was indeed a function of volumes of the tank that were still at higher than background conductivity.

Derivation of F curves in this case would not have taken this poor trace recovery into account. For this reason comparisons of this nature were considered misleading and have not been presented.

If one considers that water plus tracer is entering the tank at time t=0, then after time t=n*T*, a given fraction of that water and tracer has exited the tank, while the remaining fraction is retained within the tank. The fraction of trace that remained in the tank was dependant upon the flow pattern that was established in the tank. Therefore for comparative results between Series to be meaningful this fraction of un-recovered trace needed to be represented. For this reason comparative curves have been presented which represent the cumulative percentage recovery of the inlet injected trace over dimensionless time *T*. *T* is defined as elapsed time in seconds divided by the model mean nominal retention time for that test. In the subsequent chapter these are described as water exchange curves.

The mean retention time for each test was determined by calculating the average operational depth of the model during the whole period of the test from the time series on the depth and the mean flowrate during the period of the test. This provided a means of direct comparison between geometries that resulted in good recovery as a function of good mixing and those which resulted in poor trace recovery as a function of dead areas.

4.7.3 Dead areas, plug and mixed flow fractions

F curves were used in conjunction with the Antoniades (1982) multi parameter model to predict dead, plug and mixed flow fractions.

Using the form of the **F** curve described by equation 2.13 and taking logarithms, plots of ln(1-F(t)) against t/T were prepared for the steady state tests results. The least squares line through the straightest portion of the curve was determined and used to calculate the fractions of dead space (m), plug flow (p) and completely mixed flow (1-p) using equations 2.15 and 2.16 respectively. A not a typical plot with the associated linear regression analysis is shown in Figure 4.11. As discussed in Chapter 3, selection of the straightest fraction of the curve and inclusion or omission of the initial or final part of the generated curve can lead to large variation in the results. In the subsequent results section this will be referred to as the *m-p* model.

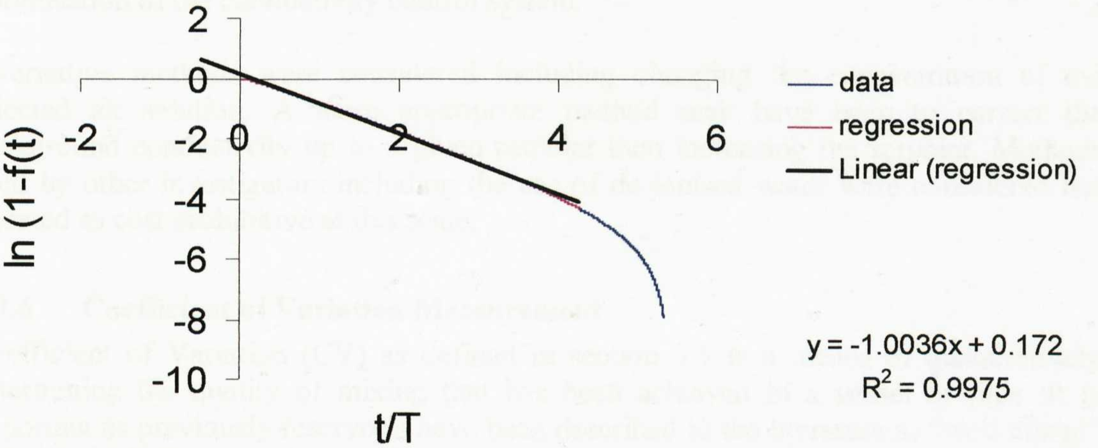


Figure 4.11 - Graph of ln(1-F(t)) against t/T

Due to the potential for analytical error using the m-p model an alternative simplistic approach to estimation of dead volumes was evaluated. For each set of steady state tests the mean or centroid of the resulting RTD ($\bar{t}$) and the variance (σ) were determined. For steady state conditions the nominal retention time, T, should be equivalent to $\bar{t}$. In cases where $\bar{t}$ was less than T, this was taken to indicate that parts of the volume of the tank where not being utilised, i.e.: a means of evaluating dead volume. In the subsequent results section this will be referred to as the t_{mean} model.

All of the steady state tests were run for periods in excess of 5 nominal retention times. Individual tests were repeated a minimum of twice to provide assurance that the resulting RTD curves were representative.

4.7.4 Dispersion and mixed tanks in series models

The dispersed plug flow model and the mixed tanks in series models as defined by equation 2.11 and 2.12 respectively were also applied to the steady state results. Resulting in an evaluation of dispersion number and number of mixed tanks in series for each RTD curve generated.

4.7.5 Step tests

Step tests were conducted on the majority of the square tank series evaluated. The main aim for conducting the step tests was to evaluate the steady state concentration variation within the tank and calculate the coefficient of variation CV.

The method used for the step tests was to take the water supply from the model directly from the WTW supply. The model was operated under steady state conditions for several hours. Then the model source water was switched to conductivity corrected supply. Upon analysis of the traces it became apparent that there were changes in the step concentration and the results were not consistent. This may have due to the initial variation in concentration of the supplied water. Or the concentration of the salt solution used 0.010 mol/l. Indeed many of the step tests were conducted during the period of optimisation of the conductivity control system.

Alternative methods were considered including changing the concentration of the injected alt solution. A more appropriate method may have been to correct the background conductivity up to a given setpoint then increasing the setpoint. Methods used by other investigators including the use of de-ionised water were considered but rejected as cost prohibitive at this scale.

4.7.6 Coefficient of Variation Measurement

Coefficient of Variation (CV) as defined in section 3.5 is a means of quantitatively determining the quality of mixing that has been achieved in a vessel or pipe. It is important as previously reservoirs have been described in the literature as "well mixed" without any indication of actual concentration variations that can occur across the vessel cross section. Reservoirs are increasingly being considered as potential blending points in the distribution. Hence it is important to gain an understanding of the macromixing and mixture quality that may be achieved with different designs.

Using multiple internal measurement points and step tests provides the most representative means of calculating CV. The poor repeatability of the initial step tests conducted indicated that these tests would not produce reliable CV calculations. Indeed the variability between repeats tests was such that statistical analysis between different series indicated that differences in CV were not statistically significant.

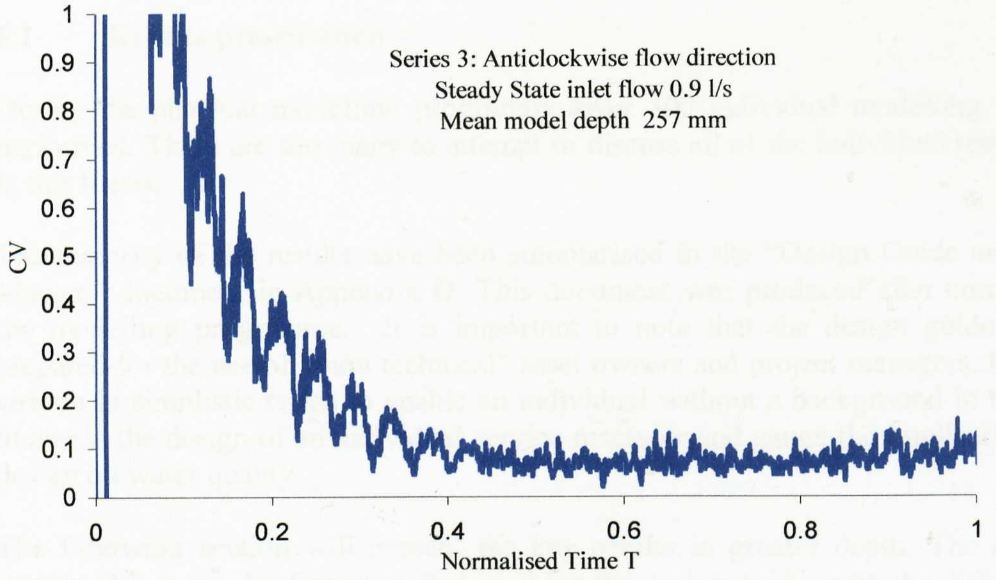


Figure 4.12 - Graph of CV versus normalised time for a single steady state series 3 experiment.

Due to the time constraints and the extensive scope of the modelling programme, step tests were not conducted for the rectangular and circular tank tests. Instead CV was calculated over time using equation 2.21 for all of the steady state tests. This involved calculating the CV from the time series conductivity traces for the internal tank probes only. From this a graph of CV versus time was plotted. A typical example is shown in Figure 4.12.

The time to achieve mixing was taken as the time to achieve the minimum sustainable CV.

This method proved to be more consistent. In the subsequent results section all of the CV and mixing times presented have been calculated in this manner. It should be noted that this is not the ideal method of determining CV. During the steady state tests the tracer is constantly being washed out of the model and diluted by the incoming flow. Consequently the final values of CV quoted should not be considered as absolute values, but an indication of the concentration variation within the model.

Other investigators have used a pulse injection to evaluate mixing in reservoirs. However this has generally been conducted under fill and not steady state conditions.

5 Results

5.1 Results presentation

During the physical modelling programme over 300 individual modelling tests were performed. There are too many to attempt to discuss all of the individual tests in depth in this thesis.

The majority of the results have been summarised in the "Design Guide and Retrofit Manual" document in Appendix D. This document was produced after completion of the modelling programme. It is important to note that the design guide has been prepared for the use of "non technical" asset owners and project managers. It has been written in simplistic terms to enable an individual without a background in the subject to assess the design of an individual service reservoir and gauge the implications of the design on water quality.

The following section will present the key results in greater depth. The results are presented in a similar format to that used for the design guide, with the difference that the design guide is presented in order of performance. For ease of referencing the design guide is referred to in the subsequent section schematics. Individual inlet and outlet arrangements for a given tank geometry are given a Series label, defining a "Series" of tests.

Normalised concentration – time curves are used in most instances to compare the age distribution of fluid leaving the model.

5.1.1 Sections 5.2 to 5.4: Rectangular tanks

The tanks in these sections are segmented initially by aspect ratio. The results for tanks with aspect ratio 1:1 will be discussed in some depth. The rectangular tank results will then be presented in terms of the implications of changing the aspect ratio on the resulting flow pattern and performance of particular inlet and outlet geometries or Series.

Twin compartment tanks have not been modelled as whole tanks during this programme. The results from the modelling may be applied to specific compartments of twin compartment tanks if one considers each compartment as a separate tank with individual inlet and outlet arrangements. One might anticipate that there will be differences in performance due to cross over flow where separating walls are not full height. This will be discussed in more depth in subsequent sections.

5.1.2 Sections 5.5 to 5.6: Circular tanks

Circular tanks are segmented into single or twin compartment tanks. Twin compartment tanks were modelled as whole tanks during this programme due to the practical ease of tank segmentation and maintaining both halves of the model sides full of water.

5.2 Aspect ratio 1:1 – square tank, submerged horizontal straight pipe (HSP) inlets

The model was set up with a length of 3418 mm and a width of 3418 mm. The operational depth of the model varied throughout the square tank tests from 242 mm to 360 mm. For steady state tests the inlet flowrate was set at values between 0.12 and 0.9 l/s. For the majority of the tests the inlet pulse volume was 200 ml/s and the pulse duration was typically 5 seconds. The configurations trialed in this section are shown in schematics in Figure 5.1. The subscript in italics cross-references the position in the design guide Appendix D.

5.2.1 Series 1: Horizontal straight pipe inlet parallel to side wall, outlet directly opposite

This design was found to be a commonly occurring geometry, and is typically of one half of many symmetrical twin compartment reservoirs. Commonly the inlets and outlets of each compartment are housed in common pump houses, such that each half is a mirror image of the other.

Steady state tests:
In all of the steady state tests the same general flow pattern was established, as shown in typical dye tests photographs depicted in Figure 5.2. The observed flow pattern was confirmed by the order and magnitude of response of the model internal conductivity probes and the resulting RTD that was generated in each instance.

The inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. As the inlet jet travels around the tank it expands and gradually entrains more of the surrounding fluid. A large area of slow moving water is established in the centre of the tank where older water accumulates and any settlement is likely to occur due to the lower fluid velocities.

Typical RTD curves are shown in Figure 5.3, which show multiple recirculations before the trace begins to decay exponentially. The traces indicate the consistency of repeat steady state tests.

The central dead zone in the tank remains as the level in the tank is altered and results in poor overall mixing and long times to achieve complete water exchange. A typical water exchange curve is shown in Figure 5.4, where only 75% of the water has exchanged in 4 nominal residence times.

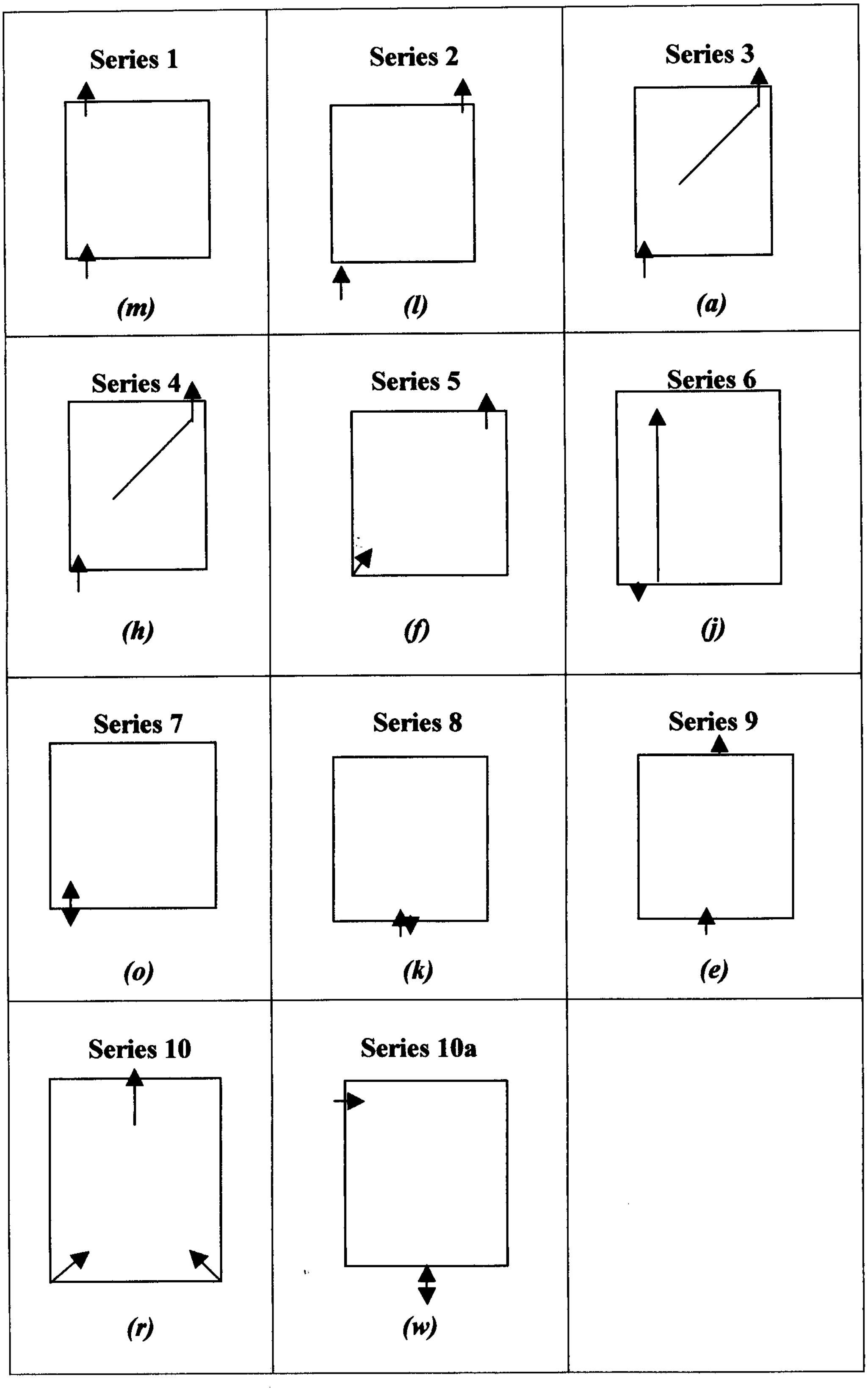
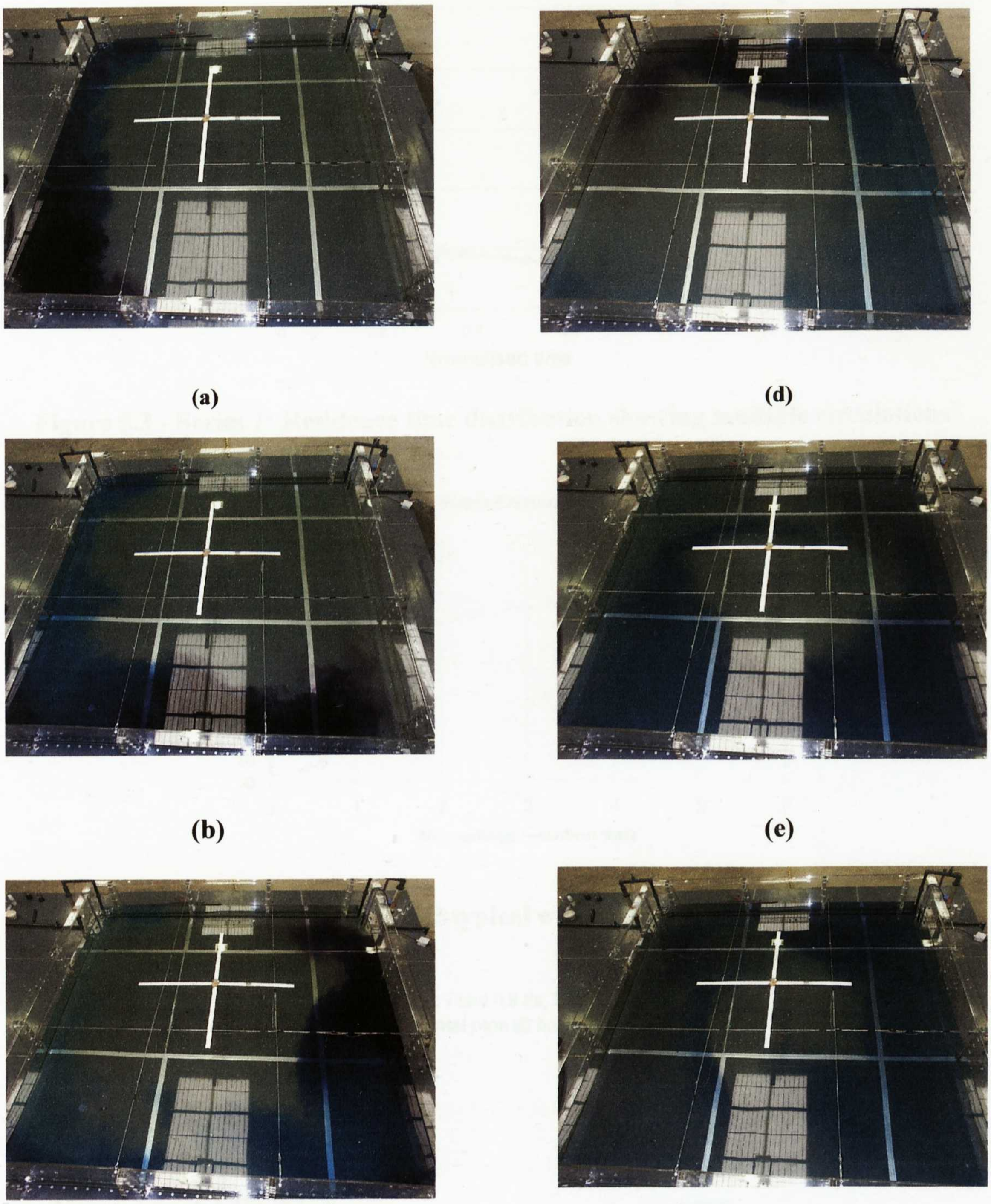


Figure 5.1 - Tank L:W ratio of 1:1 : Low level HSP inlet / outlets



(a) (d)

(b) (e)

(c) (f)

Figure 5.2 - (photos a to f)
Series 1: typical dye tests: inlet and outlet directly opposite

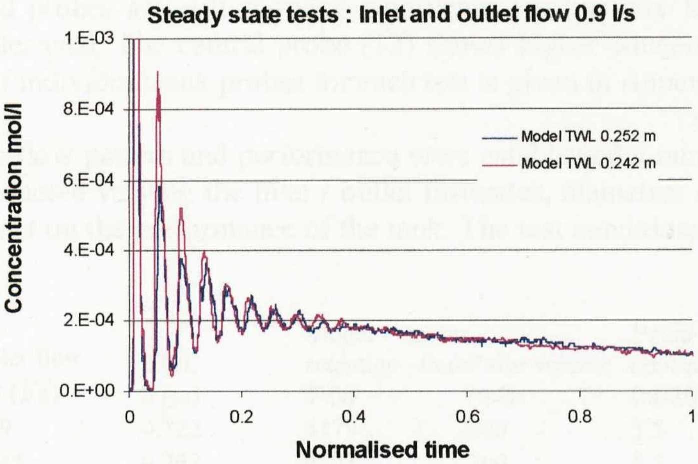


Figure 5.3 - Series 1: Residence time distribution showing multiple circulations

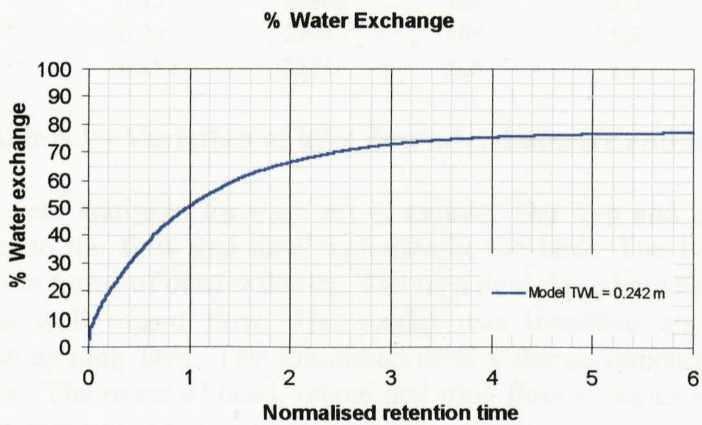


Figure 5.4 - Series 1: typical water exchange curve

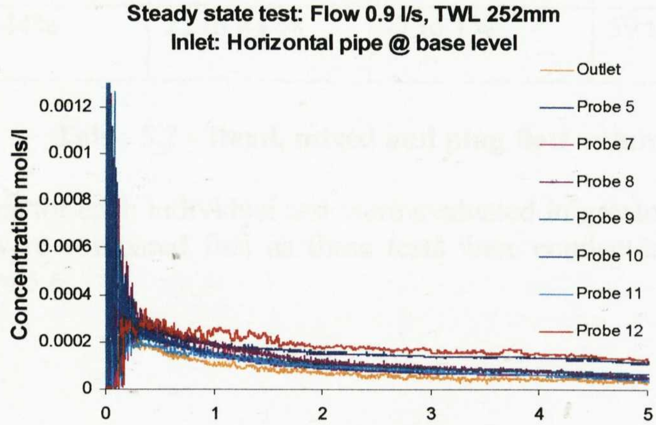


Figure 5.5 - Series 1: model internal tank probe response

From analysis of the model internal tank conductivity probes (Figure 5.5), it is evident that the central probes are still showing significant conductivity long after the outlet response has decayed. The central probe (12) shows higher concentrations after 16 T. The position of individual tank probes for each test is given in Appendix B.

After the basic flow pattern and performance were established a number of steady state tests were conducted varying the inlet / outlet flowrates, diameters and model depth to assess the impact on the performance of the tank. The test conditions are summarised in table 5.1.

Test	Inlet flow Q (l/s)	TWL h (m)	Model mean retention time T (s)	Pulse volume (ml)	Pulse concentration (mol/l)	Inlet diameter d (mm)
a	0.9	0.322	4179	200	5.5	25.4
b	0.45	0.262	6801	200	5.5	12.7
c	0.8	0.262	3826	200	5.5	12.7
d	0.9	0.262	3400	200	5.5	38.1
e	0.12	0.25	24339	20	5.5	25.4
f	0.2	0.25	14603	100	5.5	25.4
g	0.4	0.25	7301	100	5.5	25.4
h	0.9	0.252	3271	200	5.5	25.4

Table 5.1 - Variation of inlet flowrate, diameter and level

The tracer tests were analysed for each set of results. The m-p and t_{mean} models were used to characterise the flow and dead volumes in the tank. The two methods gave consistent results in terms of dead volumes. The m-p model predicted that the remainder of the tank was well mixed flow. The model was therefore not interpreting the recirculating flow as plug flow. The calculated dead volumes concurred with the flow visualisation tests. The range of dead, mixed and plug flow volumes calculated for this Series of tests are summarised in Table 5.2.

T_{mean}	m-p model		
Dead Space	Dead Space	Plug Flow	CSTR
22 - 44%	22 to 44 %	-7 to 1%	59 to 78 %

Table 5.2 - Dead, mixed and plug flow volumes

The RTD curves for each individual test were evaluated in greater depth. Tests a and e through to h were compared first as these tests were conducted with the same inlet diameter, Figure 5.6.

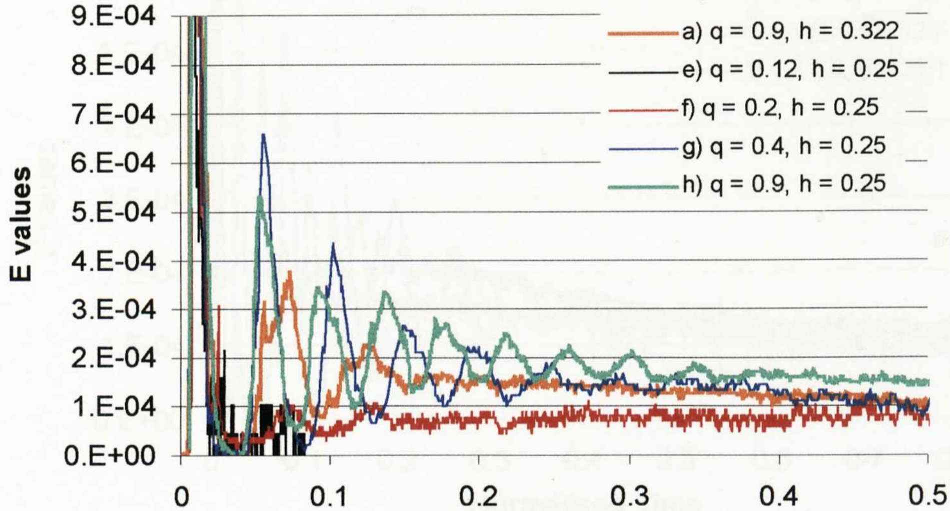


Figure 5.6 - Variation of inlet flowrate and tank depth

The number of multiple circulations before exponential decay appears to be influenced by the operational depth and the inlet velocity.

At the higher operational depth, test a, the number of re-circulations are significantly reduced. At the lower inlet velocities the number of circulations are again reduced.

Trace e, was not discernable after the first circulation, possibly due to the volume of trace injected, however using a larger dose would have compromised the inlet velocity and using a stronger concentration may have produced density effects.

Trace f starts to decay after 3 circulations; it is possible that further circulations were not discernable as a result of the lower initial pulse volume. However the background was poor during this test and started to increase after the third circulation, which is indicated by the poor final coefficient of variation and longer mixing time.

The outlet RTD traces from tests b, c and d were compared, Figure 5.7, and all showed multiple circulations. Trace d was notable in terms of the longer time it took to achieve exponential decay of the outlet curve, 0.587 T.

The model length to depth ratio was 13.6:1 for tests b to h and dropped to 10.6: 1 for test a. Comparison of these results with the work of Morrison (1999), full scale CFD simulations of a similar inlet and outlet arrangement on a tank with aspect ratio 1.1:1 and tank length to depth ratio 4.4:1 indicates the same number of circulations in the tank prior to exponential decay.

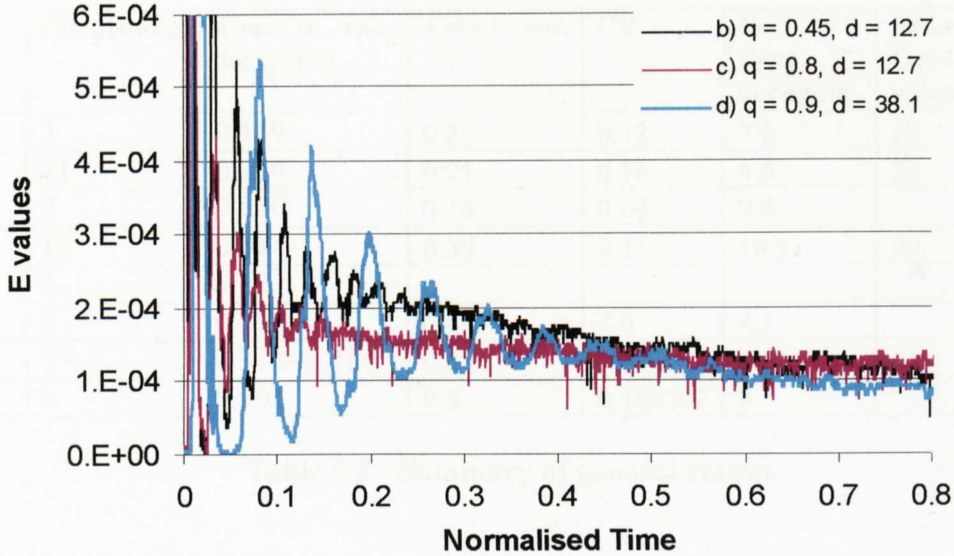


Figure 5.7 - Variation of inlet diameter and flowrate, fixed tank depth 0.262 m

The results from individual tests are summarised in table 5.3 below. In general the normalised time for each tracer to start to decay and the time taken to reach a stabilised coefficient of variation for each test were similar.

In general using the point at which exponential decay starts in the outlet curve to predict the time to achieve mixing would appear valid. However it should not be assumed that the total volume of the tank is "well" mixed. In this Series significant volumes of the tank contain slower moving water.

As a consequence of the large dead volumes, final recovery of the inlet pulse was ubiquitously poor. Time to achieve water exchange was protracted as a function of the rate of exchange of water with the central quiescent zone, figure 5.8 below.

Jet mixing models were applied to the data to determine whether previous work in this area was relevant to models with steady state inlet and outlet flow. The Fosset and Prosser (1949), Van de Vusse (1959), Fox and Gex (1956) and Okita and Oyama (1963) models were applied and the correlations given in Figure 5.9.

In this instance the Okita and Oyama (1963) model produced a better correlation than the Fox and Gex (1956), Prosser (1949), or Van de Vusse (1959)model. The correlation coefficient, K was equal to 15.1, which is different to that determined by Okita and Oyama (1963) where K = 4.7 and Grayman (1999) where K=7.1. This is likely to be attributable to the different experimental techniques used and the measurand used for mixing.

Test	Circulations	Time to exp. decay (T)	Time to mix CV	CV	% short circuiting	Estimated Dead volume
a	3	0.149	0.2	0.12	8.9	28
b	11	0.274	0.21	0.12	4.5	23
c	7	0.160	0.18	0.08	2.8	
d	10	0.587	0.36	0.11	19.9	30
e	1	0.12				
f	3	0.157	0.4	1.9	4.7	
g	7 – 8	0.318- 0.366	0.3	0.3	5.4	44
h	9	0.361	0.3	0.146387	8	

Table 5.3 - Summary of general results.

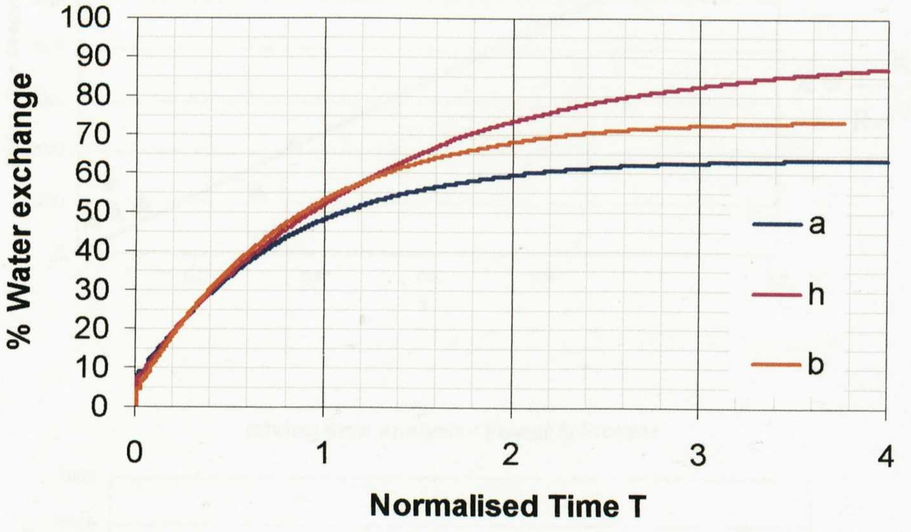
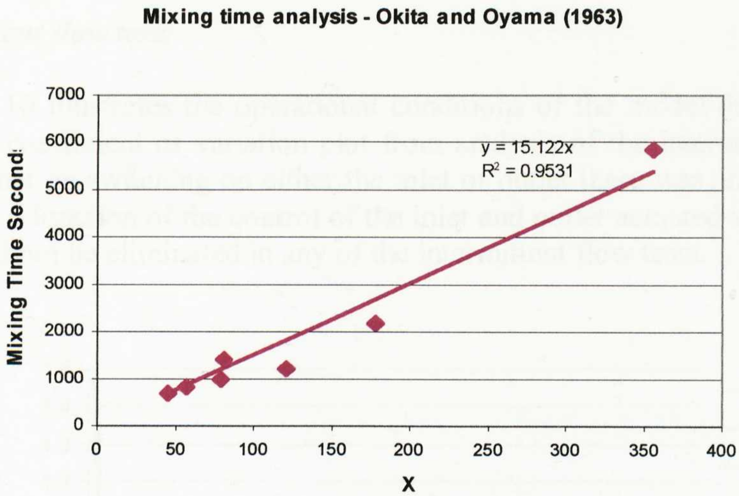
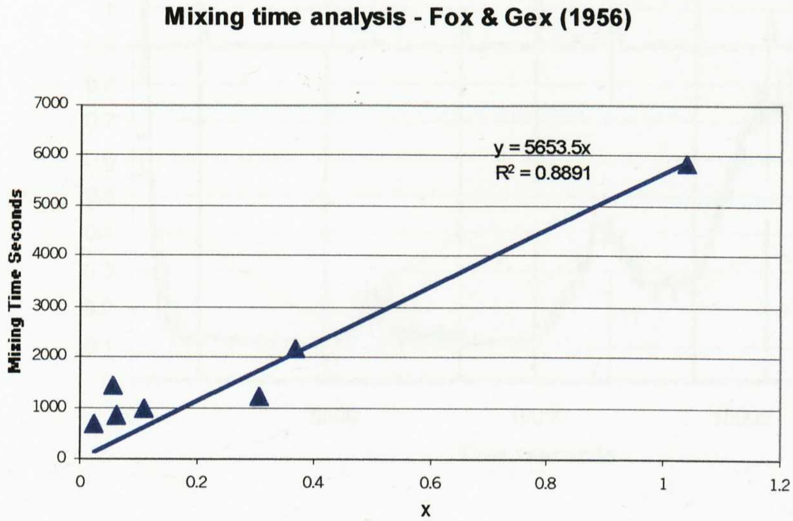


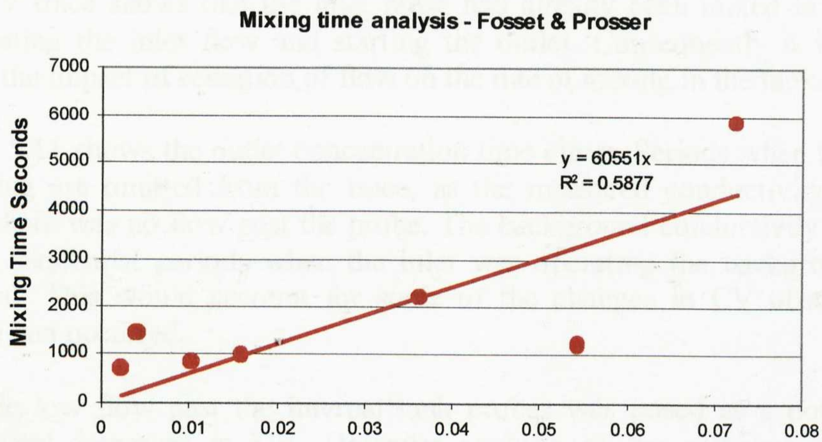
Figure 5.8 - Water exchange curves a,b,h



$$X = \frac{KH^{1/2}D^{3/2}}{M^{1/2}}$$



$$X = \frac{KH^{1/2}D}{Re^{1/6}\,M^{2/3}g^{1/6}}$$



$$X = \frac{KD^2}{M^{1/2}}$$

Figure 5.9 - mixing model correlations

Intermittent flow tests

Figure 5.10 illustrates the operational conditions of the model during the test and the resulting coefficient of variation plot from analysis of the internal model probes. It is notable that on switching on either the inlet or outlet there was an initial surge in flow. This was a function of the control of the inlet and outlet actuated valves and is a feature that could not be eliminated in any of the intermittent flow tests.

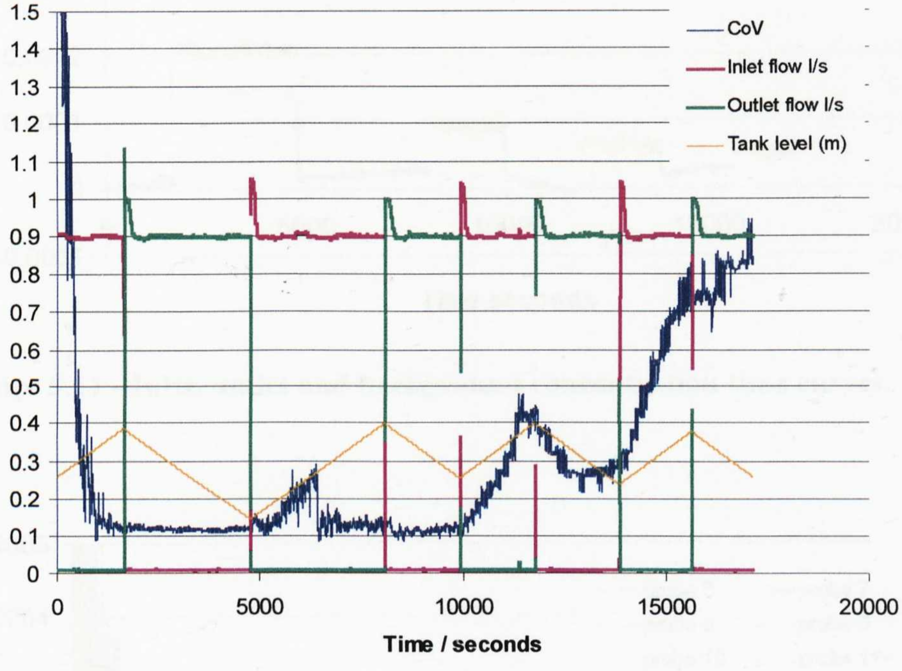


Figure 5.10 - Inlet and outlet flow, tank level and CV.

The CV trace shows that the inlet pulse had already been mixed in the tank prior to terminating the inlet flow and starting the outlet. Consequently it is not possible to assess the impact of cessation of flow on the rate of mixing in the tank.

Figure 5.11 shows the outlet concentration time curve. Periods when the outlet was not operating are omitted from the trace, as the measured conductivity drifted upwards when there was no flow past the probe. The background conductivity curve shows that during sequential periods when the inlet was operating the background conductivity changed. This would account for some of the changes in CV observed after initial mixing had occurred.

Possible low flow past the internal tank probes was posed as a potential reason for subsequent increases in CV. However analysis of the response of the individual conductivity probes during periods when the inlet was not operational showed that there was no general tendency for the measured conductivity to drift upwards so this would not explain the increase in CV. This only occurred during the period (t=12000 to 14000) for all of the internal probes. It does however suggest that there was flow passing all of the internal tank probes throughout the test

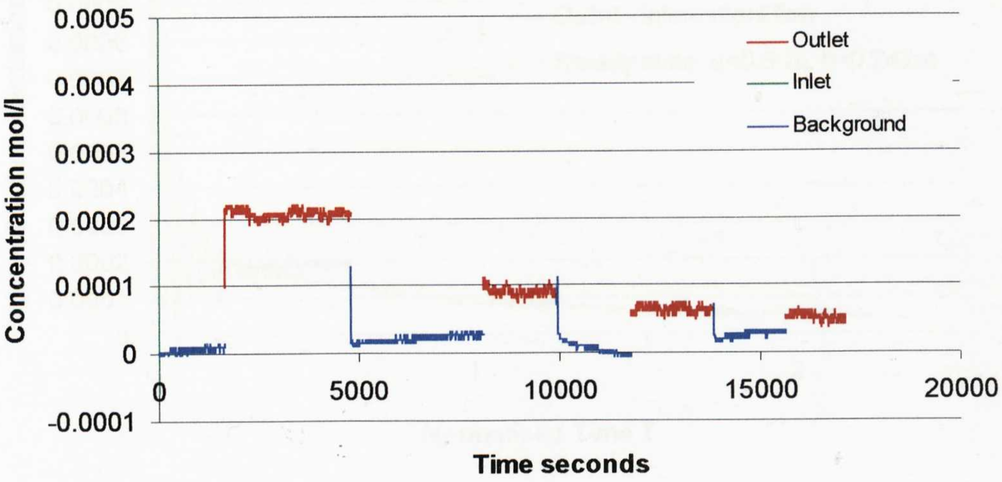


Figure 5.11 - Inlet, outlet and background concentration time curves.

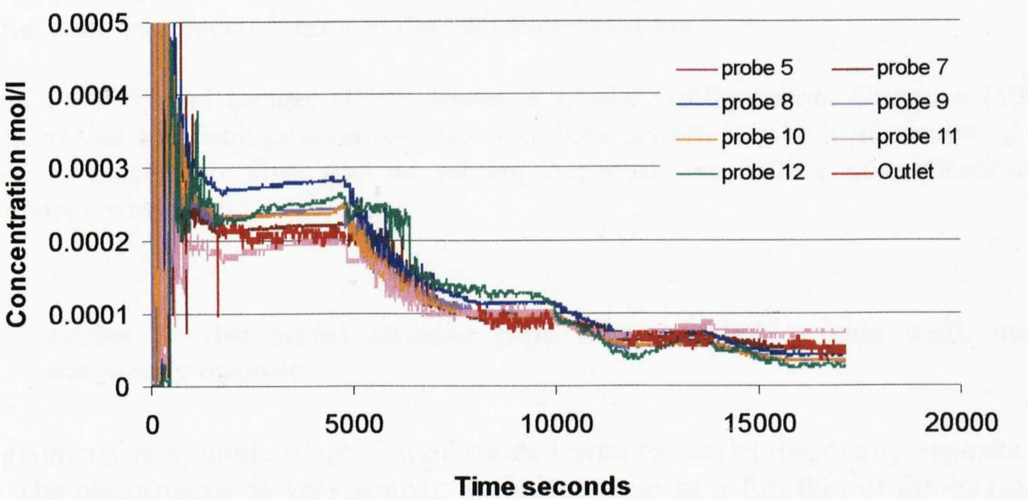


Figure 5.12 - Internal tank probes concentration time curves

Normalising the concentration time curves, based upon the nominal retention time for the whole test period and comparing the residence time distribution curve with the steady state tests, one can see that although the initial shape of the traces are different the curves are similar. Figure 5.13.

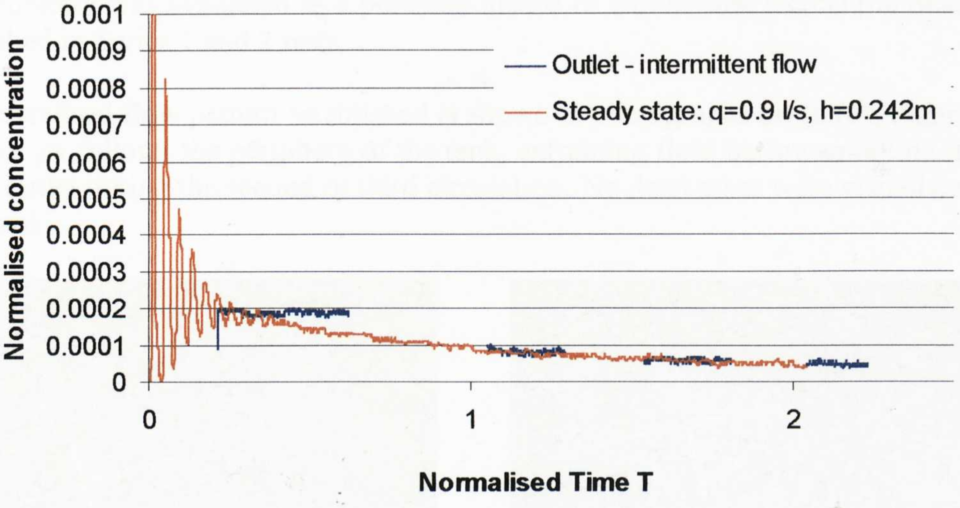


Figure 5.13 - Comparison of steady state and intermittent flow RTD's

In this instance the normalised time to achieve complete water exchange does not appear to be unduly influenced by the intermittent operation. This may be attributable to the long periods of fill then draw (1/2 T) and the degree of mixing that was achieved after the trace was injected, prior to the inlet flow cessation.

Grayman (1999) and Langer (1970) trialed a similar configuration: Grayman (1999) concluded that the configuration resulted in a flow pattern in which the centre of the reservoir received no flow and no mixing occurred. No further quantification of performance was given.

5.2.2 Series 2: Horizontal straight pipe inlet parallel to side wall, outlet diagonally opposite

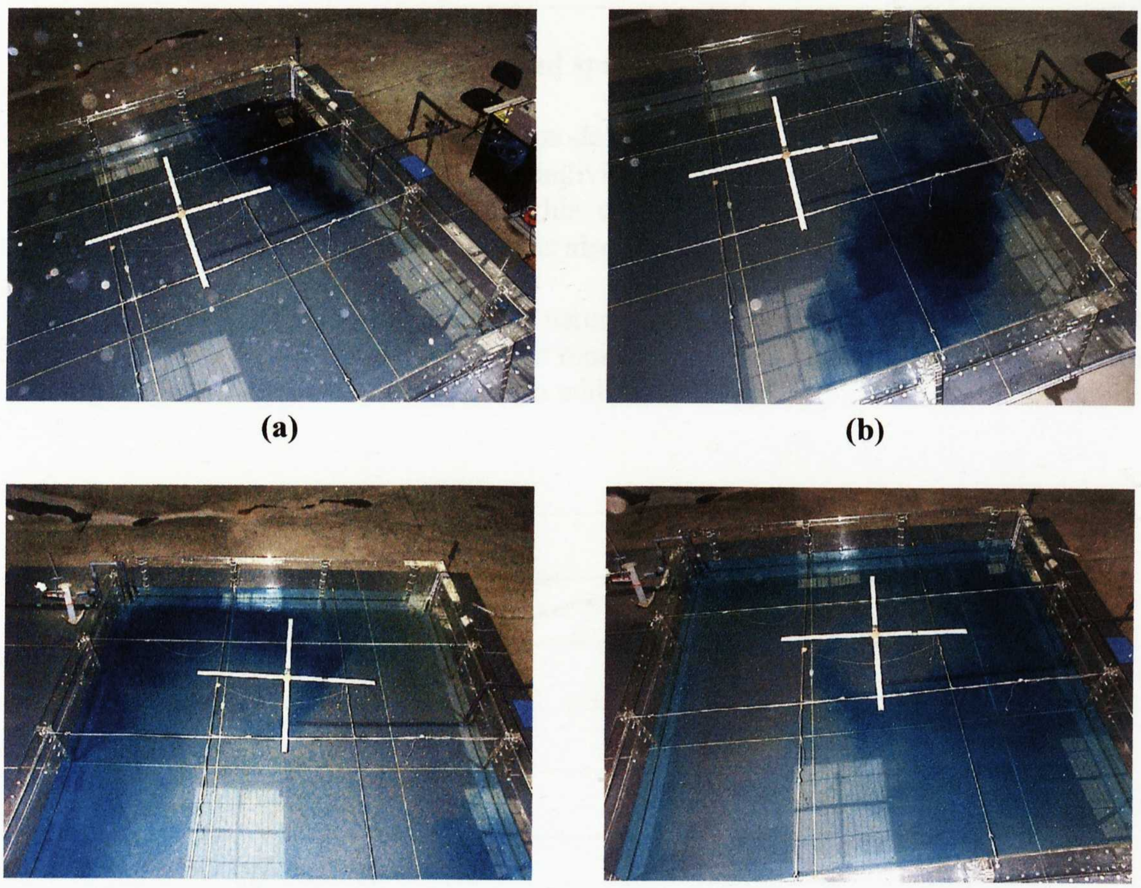
This geometry is a simple adaptation of Series 1 with the outlet diagonally opposite the inlet. The performance is very similar; variations arise as a function of the increased distance between inlet and outlet. Thus t_0, the time to the first circulation increased and the % short-circuiting changed slightly, as a function of the increased expansion of the jet. Again this was a common inlet / outlet arrangement in reservoirs surveyed, possibly due to a design requirement to maximise the distance between the inlet and outlet.

In practice tanks such geometries have been associated with a range of water quality issues such as erratic chlorine residuals and bacteriological failures. Refer to case studies in Appendix D.

5.2.3 Series 3: Horizontal straight pipe inlet parallel to side wall, outlet from the centre of the tank.

This geometry was evaluated as a potential means of eliminating the central dead areas established in Series 1 and 2 tests.

The generalised flow pattern established is shown in photographs (a) to (d), Figure 5.14. The inlet jet follows the periphery of the tank, entraining fluid before spiralling into the central outlet during the second or third circulation. No dead areas were visually evident in the tank.



(a) (b) (c) (d)

Figure 5.14 - Dye Tests: Horizontal straight pipe inlet, central outlet

Steady State Tests:
In excess of 15 individual tests were conducted with this general configuration. Various iterations of the steady state conditions were trialed which included altering the operational depth, the inlet flowrate and direction of rotation of the inlet jet (clockwise / anticlockwise). In all cases there was a minimum of one complete circulation of the tank before any of the trace began to spiral into the centrally positioned outlet.

Analysis of the RTD curves confirmed that dead areas were negligible, and short–circuiting was eliminated, table 5.4. Sustainable CV's of less than 0.1 were achieved, indicating 90% mixing was achieved.

	T_{mean}	m-p model		
Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
Negligible	0	-16% to –5%	13 to 20 %	91 to 99 %

Table 5.4 - Series 3: Dead space, plug and mixed flow

It should be noted that with the m-p model the sum of the dead, plug and mixed fractions equals unity, however for any individual test a given fraction can actually be greater than unity or negative as in this case. Although the model is predicting completely mixed tank characteristics, it is also indicating significant plug flow.

In effect the flow path is plug flow in nature, with dispersion and mixing at the jet boundaries. As a result, water exchange is rapid, figure 5.15 and confirmed by complete and rapid visual clearance of the dye from within the model.

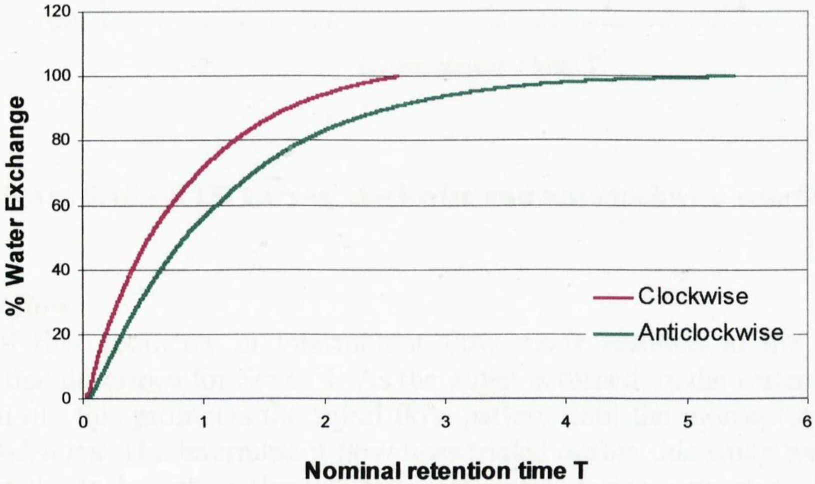


Figure 5.15 - HSP inlet central outlet

There was no discernable difference in performance during the dye tests when the model was operating with a clockwise or anticlockwise inlet jet. Subsequent analysis of the RTD curves showed that anticlockwise rotation produced a smoother RTD curve with a slightly longer period to recover the trace. This trend was evident on repeat tests. Although this apparent effect does not have a critical impact on the performance of the geometry in terms of achieving effective mixing and eliminating dead areas.

It was not confirmed during this study whether this was attributable to some aspect of the physical model or a function of the rotation direction alone.

Existing tanks may lend themselves to simple modification to promote mixing in one direction. To introduce the inlet jet in the other direction may require more extensive pipework modifications. The placement of the outlet pipework within the tank in this instance did not appear to have an impact on the flow pattern. This may not be assured with other pipework configurations.

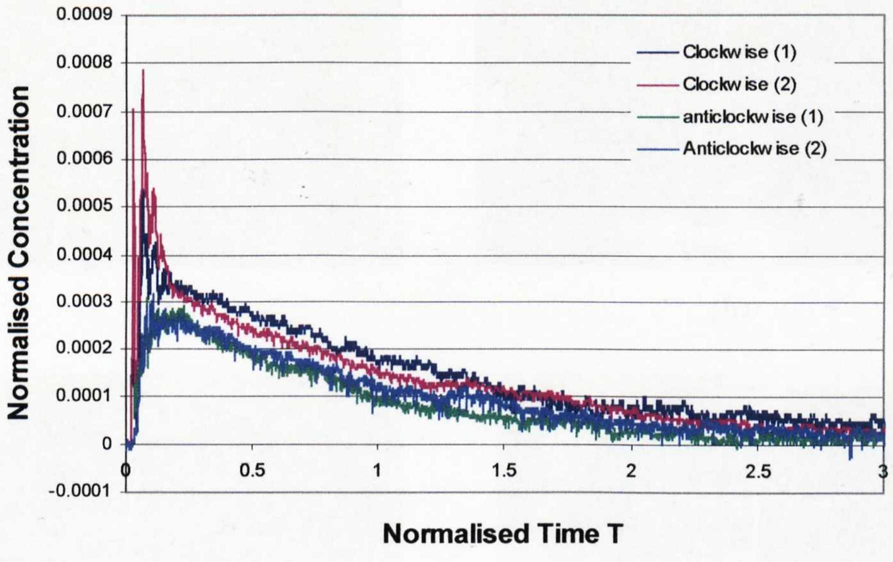


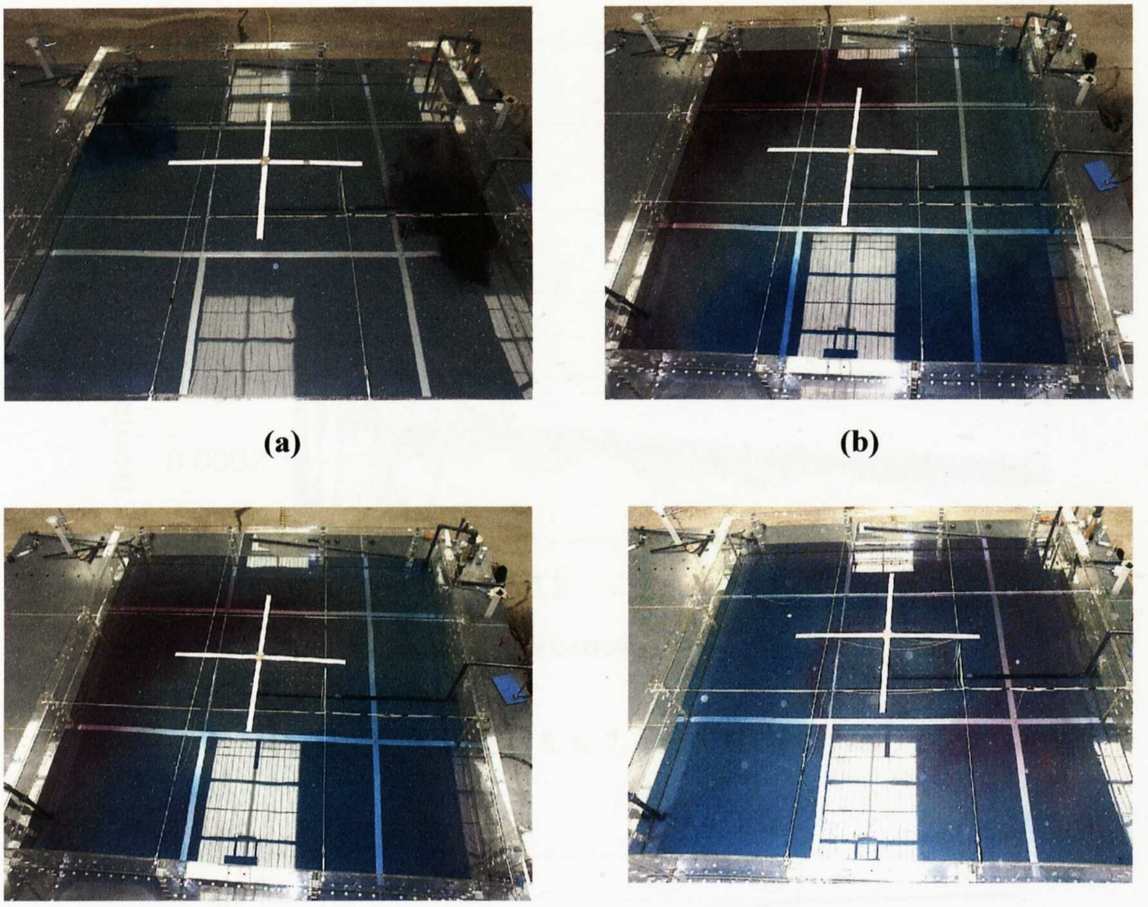
Figure 5.16 - RTD curves, clockwise and anticlockwise rotation

Intermittent flow.
Operation of this geometry in intermittent flow mode resulted in the flow pattern reverting to that described for Series 1. As the outlet is turned on the water in the central area is taken out this promotes the spiral flow pattern until the momentum of the inlet circulation subsides. The intermittent flow tests trialed during this study were limited. It is likely that the tank will go through transient states during extremes of intermittent flow operations.

5.2.4 Series 4: Multiple HSP inlets parallel to side wall, outlet taken from the centre of the tank.

The geometry in Series 3 was adopted to evaluate whether the performance could be maintained with multiple inlets. Figure 5.17 shows dye tests that were conducted with different coloured dyes injected at two separate locations at the same time. In this instance the plugs of dye followed each other in sequence for two circulations before fusing and eventually becoming mixed, confirming the plug nature of the flow.

Placement of the inlets adjacent to each other resulted in rapid blending of the two dye streams. The flow pattern then progressed around the tank in a similar manner to that depicted in Figure 5.14.



(a) (b)

(c) (d)

Figure 5.17 - multiple inlet dye tests: Inlet flow (1&2) 0.45 l/s

5.2.5 Series 5: Horizontal straight pipe inlet directed diagonally across base of the tank towards outlet.

Analysis of the RTD curve for this arrangement showed good mixing, no significant dead areas, no short-circuiting and good water exchange, Figures 5.18 and 5.19. The RTD shows no re-circulation although strong recirculation patterns occur within the tank. The inlet jet travels diagonally across the tank and splits into two recirculation cells. What is notable is that the leading edge of the flow does not reach the outlet before the flow splits and forms the two re-circulation cells. So there is no short-circuiting. Figure 5.20. The trailing edge of the flow eventually reaches the corner where the outlet is situated. Again the m-p model predicts predominantly mixed tank characteristics with an indication of plug flow.

The sustainable CV was 0.15 and the time to achieve mixing was rapid, 0.08T.

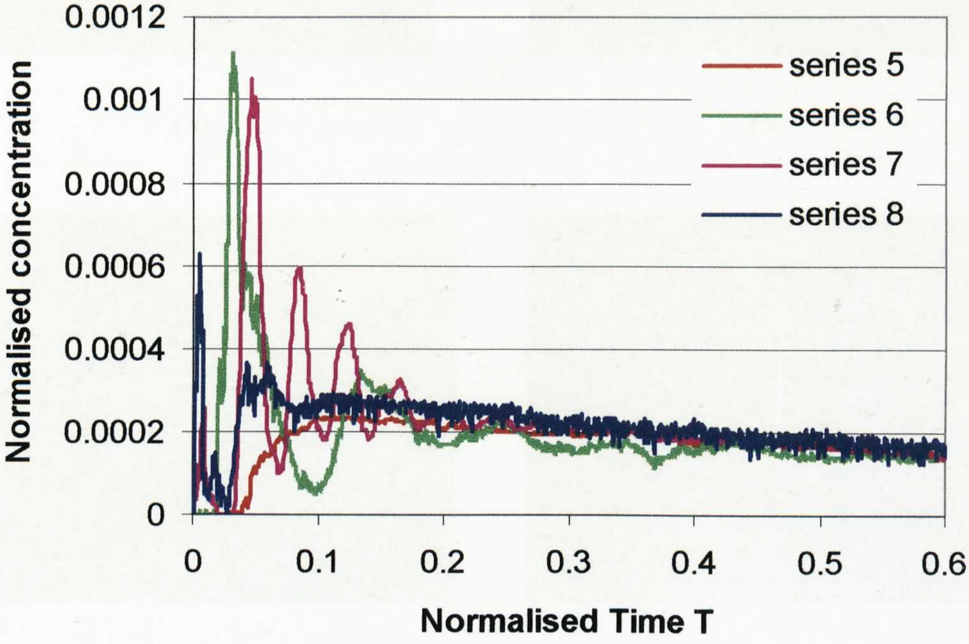


Figure 5.18 - Series 5, 6, 7, and 8 RTD curves.

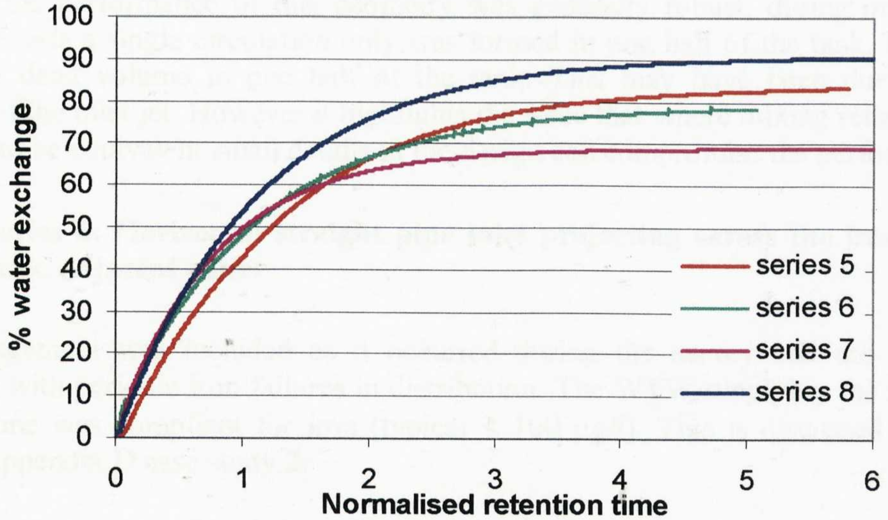
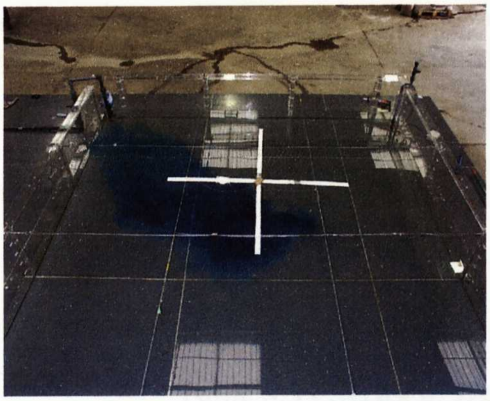
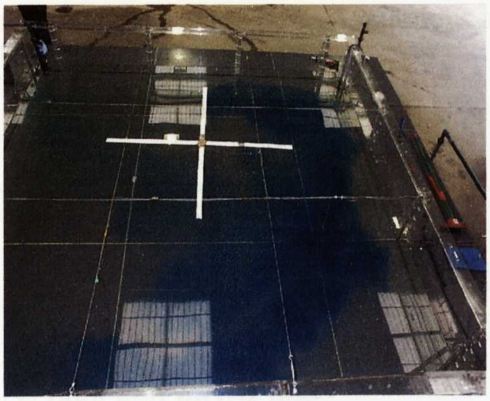


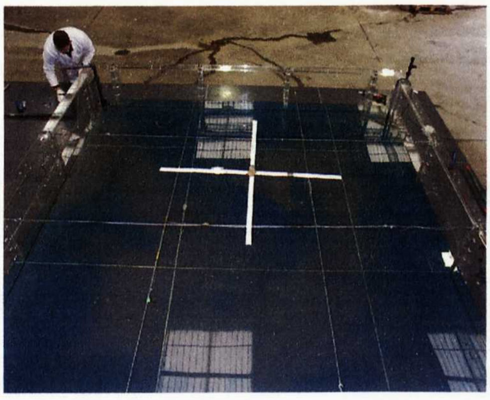
Figure 5.19 - Series 5, 6, 7 & 8 water exchange curves



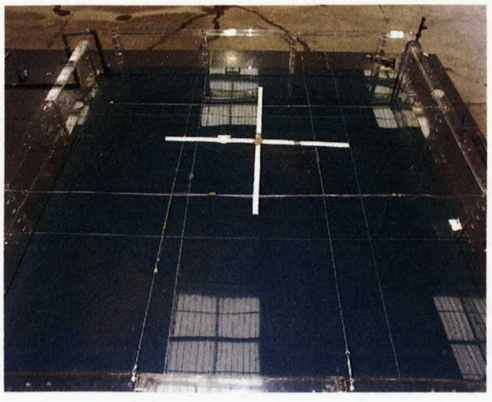
(a)



(b)



(c)



(d)

Figure 5.20 - Series 5 Dye Tests, Inlet and outlet diagonally opposite

Although the performance of this geometry was generally robust, during one of the repeat dye tests a single circulation only was formed in one half of the tank, leaving a significant dead volume in one half of the tank. This may have been due to poor direction of the inlet jet. However it highlights the issue that where mixing relies upon a flow split to be equivalent small details in the design can compromise the performance.

5.2.6 Series 6: Horizontal straight pipe inlet projecting across the base of the tank, adjacent outlet

This arrangement was included as it occurred during the survey and the site was associated with periodic iron failures in distribution. The WTW supplying the reservoir and the zone was compliant for iron (typical < 100 μg/l). This is discussed in more depth in Appendix D case study 2.

The inlet jet discharges directly into the opposite wall, which acts like an impingement plate. The flow splits forming a large dominant circulation cell and a smaller cell. The smaller circulation cell turns and joins the larger cell. This results in a central dead area.

The resulting flow pattern is similar to Series 1&2, and multiple recirculations are apparent, although reduces and variable in number (2 to 5), Figure 5.18.

	T_{mean}	m-p model		
Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
8%	8%	-6 to 5%	1 - 3%	91 to 100 %

Table 5.5 - Series 6: Dead space, plug and mixed flow

The central dead area is reduced compared to Series 1, the m-p model suggests principally well mixed flow with a tendency for dead areas.

Water exchange times are similar to Series 1 and 2, Figure 5.19. Short-circuiting is compounded by the placement of the inlet pipe across the base of the tank.

5.2.7 Series 7: Horizontal straight pipe inlet parallel to side wall: inlet and outlet common or adjacent pipe

Tanks with a common inlet / outlet pipe are frequently referred to as push pull tanks. They often occur at the extremes of the distribution network system. They fill and empty as a function of pressure fluctuation in the supplying main. Determining the volume - frequency of in and outflow can be problematic as level measurement is not always available. The resulting nominal retention times can be excessive and unquantified and these types of tanks are commonly associated with water quality issues and incidents.

For practical ease the model was arranged with the inlet and outlet adjacent then operated in steady state / intermittent flow modes.

Steady state: Adjacent inlet / outlet:
The general flow pattern was in accord with those observed in Series 1 & 2. When operating under steady state conditions the momentum of the inlet jet assures that there is minimal direct short-circuiting to the outlet, typically less than 1%.

	T_{mean}	m-p model		
Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
0.3 %	28 %	35 to 0 %	0 to 9%	55 to 100%

Table 5.6 - Series 3: Dead space, plug and mixed flow

The m-p model predicts greater variability in steady state performance. The time to achieve mixing (0.3 T), mixing achieved (CV 0.152) and water exchange curves were similar to Series 1&2, Figure 5.18, 5.19 as might be expected.

From a steady state condition as the outlet flow is increased, the propensity for flow short-circuiting increases. A transient point is then reached where the outlet flow begins to dominate / distort the flow pattern in the tank.

Intermittent flow: Push pull operation

The model was operated with an intermittent flow regime, in fill and draw mode. Inlet flow was introduced first to establish the re-circulation pattern in the tank (0.9 l/s) and then the trace was injected. Inlet and outlet flow were then alternated for ½ a nominal residence time in succession. Again mixing had taken place prior to the inlet flow being switched off. Detailed analysis of the trace was not feasible as the background conductivity drifted considerable between subsequent inlet flow phases. This was a common problem with intermittent flow tests due to the long period of operation.

A Series of 10 dye tests were conducted to evaluate how the flow pattern and mixing changed as a function of inlet flow and Reynolds number.

Test	Inlet flow l/s	Inlet velocity	Re	Comments
a	0.03	0.06	1318	No jet mixing, dye moves around tank as discrete plug, poor top to bottom mixing, stratification
b	0.05	0.10	2196	Dye moves around tank as discrete plug, slightly improved top to bottom mixing, dye trapped in boundary layer on base of the tank, stratification.
c	0.08	0.16	3514	Jet mixing occurs, Dye trapped in boundary layer on base of the tank, stratification
d	0.15	0.30	6588	Jet mixing, jet expands and entrains surrounding flow
e	0.3	0.59	13177	Jet mixing, jet expands and entrains surrounding flow, no visible boundary layer effect.
f	0.4	0.79	17569	Jet mixing, jet expands and entrains surrounding flow
g	0.4	0.79	17569	Jet mixing, jet expands and entrains surrounding flow
h	0.6	1.18	26354	Jet mixing, jet expands and entrains surrounding flow
i	0.9	1.78	39531	Jet mixing, jet expands and entrains surrounding flow

Table 5.7 - Dye tests to evaluate the implications low Reynolds number.

The most significant results from these Series of tests are that when the inlet flow is not turbulent no jet mixing occurs. The plug of injected dye moves away from the inlet, taking a similar flow path as it would have taken if turbulent. However the jet does not entrain surrounding fluid and expand but remains as a discrete plug. The model eventually appeared poorly mixed. Some of the mixing would have been attributable to diffusion.

Figure 5.21 - Dye tests inlet flow 0.03 l/s

When push pull tanks are operated with lamina inlet flow, poor macromixing and thermal stratification should be anticipated. In this instance the tank did not operate in a last in first out mode.

At inlet flowrates above 0.08 l/s (Re >3514), the inlet jet was still being trapped within the boundary layer at the base of the tank. This led to striations in dye across the base of the tank, Figure 5.22 So although the inlet jet was turbulent it was insufficient to overcome the frictional forces in the model and led to an unrealistic flow patterns.

Attempting to model at low Reynolds number can lead to unrealistic flow patterns unless the frictional forces in the model have been overcome. These will be different for models of different materials and as the surface area in contact with water / volume ratio changes.

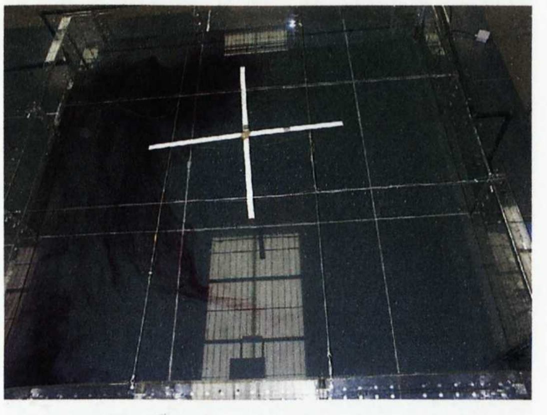
 

Figure 5.22 - Dye tests inlet flow 0.08 l/s

5.2.8 Series 8: Horizontal straight pipe inlet parallel to the side wall: mid wall.

The dominant flow pattern consists of the inlet jet traversing across the middle of the tank and then forming twin recirculation cells. Small areas of slower moving flow are found in the centre of each cell. The t_{mean} model predicted smaller dead volumes in this instance than the m-p model. The occurrence of larger dead areas in this design was primarily attributable to the asymmetry of the flow pattern. Ensuing from the position of the outlet, biasing the direction of the inlet jet, even under steady state conditions.

	T_{mean}	m-p model		
Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
1%	9%	-12 to 22	1 - 5%	71 to 100 %

Table 5.8 - Series 8: Dead space, plug and mixed flow

Mixing occurred very rapidly, 0.056 T and the degree of mixing was good, Figure 5.18, 5.19. Due to the proximity of the inlet & outlet short-circuiting is inevitable, although during steady state tests this was in fact minimal. If the tank were configured with a common inlet / outlet and the inlet flow turbulent, adequate rapid mixing could be assured. If the nominal retention time during operation were a day, a turbulent inlet flow for 1.3 hours would ensure that the tank was well mixed. With a common inlet / outlet short-circuiting would be eliminated and the resulting flow pattern would be more symmetrical, resulting in reduced potential for formation of dead areas.

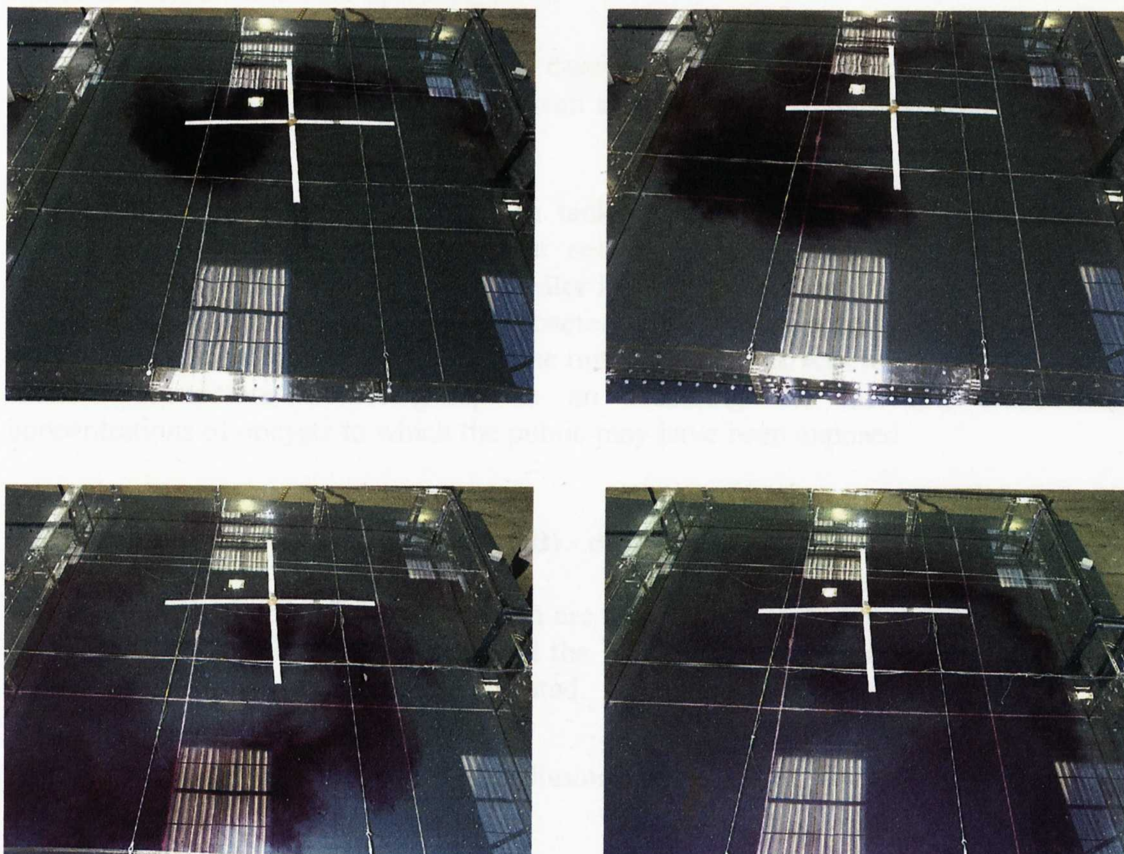


Figure 5.23 - Dye tests inlet and outlet adjacent mid-wall.

5.2.9 Series 9: Horizontal straight pipe inlet parallel to the side wall: mid wall, outlet directly opposite

This configuration is an extension of the Series 8 tests and results in a similar flow pattern. The position of the outlet ensured that more of the injected trace exited in the first circulation (13%). The estimated dead volume reduced to 4%. The degree of mixing was good, however the time to achieve mixing was greater, possibly as a function of the increased short-circuiting. In this instance variation of the outlet flow is not considered to have as profound an impact on the flow pattern as that observed for Series 8.

5.2.10 Series 10 and Series 10a: Multiple inlets and outlets

A number of multiple horizontal inlet and outlet geometries were trialed at steady state, transient state and in fill and draw mode. The geometries trailed were based on operational full-scale plant designs. The performance of an individual geometry could vary widely, from being completely mixed under specific operational conditions to having severe short-circuiting and significant dead areas under other operational conditions. Multiple potential flow patterns could exist and the flow pattern could pass through numerous transient phases as a result of relatively minor changes in inlet and outlet momentum and tank operating level.

Two examples are discussed in detail in case studies 3 and 4, Appendix C. Additional performance data on other designs is given in the Design Guide and Retrofit manual Appendix D.

After in depth analysis of several such tanks it is evident why such assets can be associated with erratic / poor chlorine residuals, THM formation, bacteriological compliance, taste complaints and dirty water incidents. Case study 4 in particular refers to a site, which had a history of periodic bacteriological failures and was associated with an outbreak of cryptosporidiosis. After the outbreak the tank was re-modelled using the transient conditions occurring up to an including the incident, to envisage concentrations of oocysts to which the public may have been exposed.

5.3 Aspect ratio 1:1, Upturned (UB) - downturned (DB) bellmouth inlets

The configurations trialed in this section are shown in schematics in Figure 5.24. For the RTD and water age curves presented the inlet flowrate and diameter are 0.9l/s and 25.4mm respectively unless otherwise stated.

5.3.1 Series 11 & 12: Upturned bellmouth inlet above TWL, outlet diagonally opposite

These were found to be commonly occurring geometries. Upturned bell mouths above TWL are commonly used when the reservoir is linked to a WTW to maintain head in the upstream processes and prevent back siphoning.

For both arrangements the inlet plunges to the base of the tank and then spreads out radially. The leading edge of the flow passes around the side walls. One jet generally travels faster than the other and reaches the outlet first. During which time the flow has reached the middle of the tank.

		T_{mean}	m-p model		
	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
Series 11	7%	0	-45	19	125 %
Series 12	10 %	0	-20	-5	125
Series 13	< 5 %	0	-10	21	89

Table 5.9 - Series 11&12,13: Dead space, plug and mixed flow

Although the results of the m-p model presented indicate some plug flow for Series 11, the results obtained for this Series were erratic (-500 % dead, 800% mixed). The time to achieve mixing was longer than for some of the horizontal inlet arrangements at 0.3 to 0.4 T and measured CV was 0.3, although initial step tests conducted indicated CV's as low as 0.15 were attainable.

Good final water exchange was achieved with no significant dead areas being calculated. However the time to achieve water exchange was longer (see Figure 5.26). A slight degree of recirculation was evident in Series 11 RTD curves.

5.3.2 Series 13: Downturned bellmouth inlet above TWL, outlet diagonally opposite

This arrangement was evaluated because it was considered that maintaining a coherent jet might improve performance. At the time of the survey there were no full-scale plants with this inlet arrangement.

The flow pattern that is established is similar to the Series 11 & 12, Figure 5.27. However short-circuiting along the side walls was reduced (< 5 %) with more flow initially spreading through the centre of the tank. Again the tank behaved predominantly as a CSTR, however recirculation patterns are more pronounced (Figure 5.25) and this is interpreted in the m-p model as plug flow behaviour (Table 5.9).

The rate of water exchange and mixing (CV 0.14) improved compared to Series 11 & 12 although the time to achieve mixing remained similar, 0.4 T (Figure 5.26).

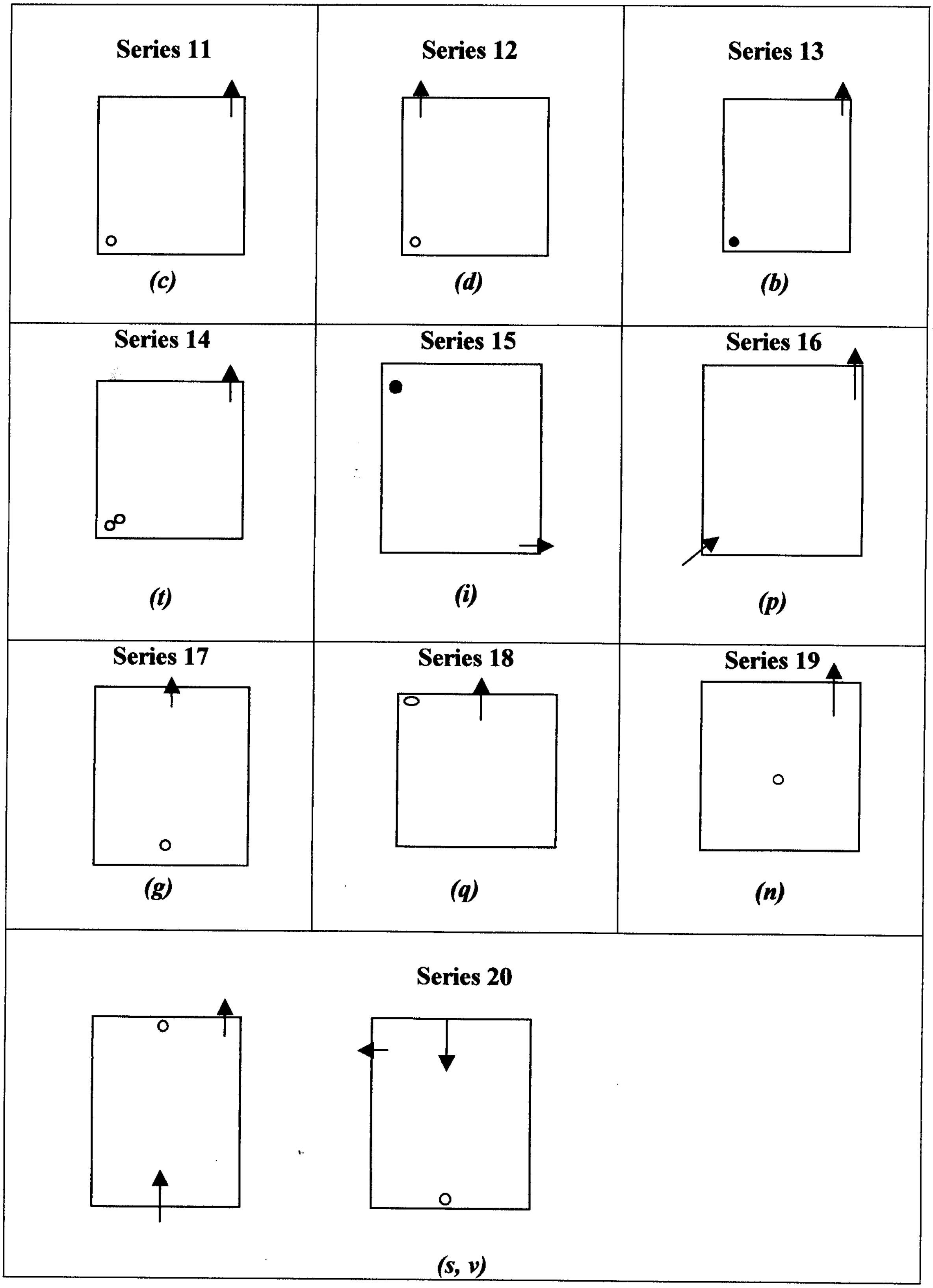


Figure 5.24 - Upturned / downturned bellmouth inlets
High-level inlets are shown in black: low level in blue

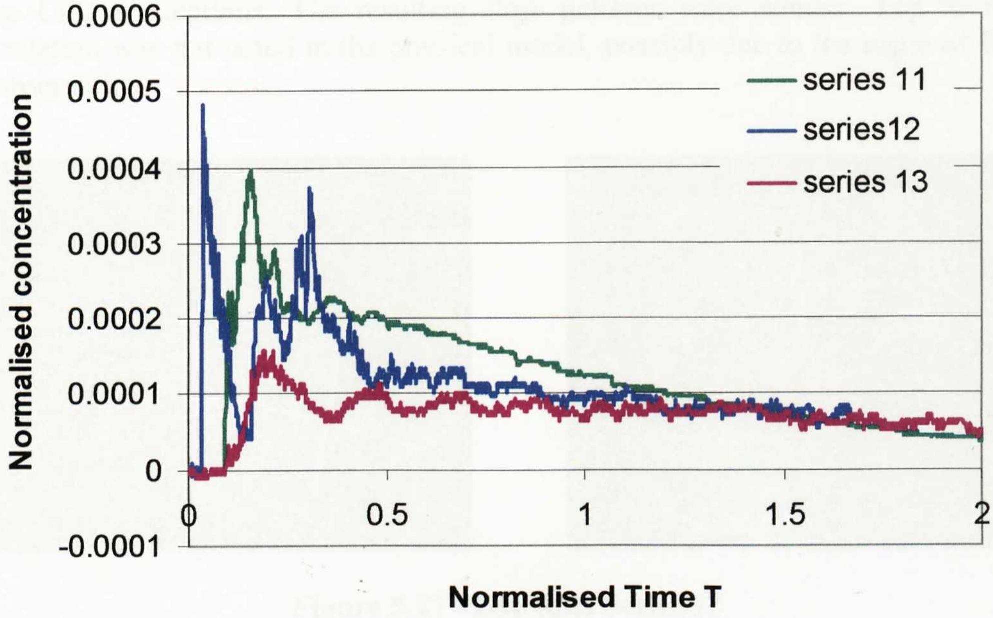


Figure 5.25 - Series 11, 12 & 13 RTD curves

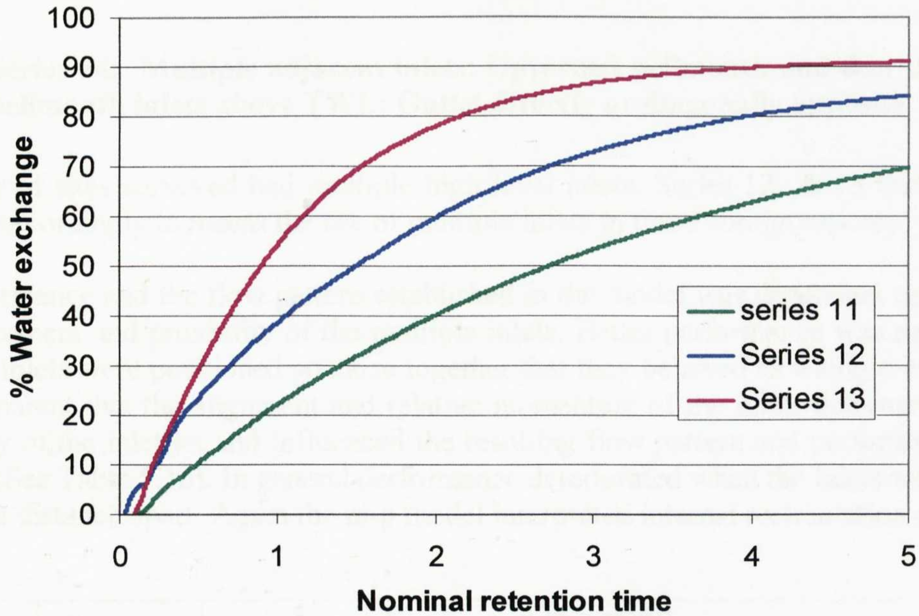


Figure 5.26 - Series 11, 12 & 13 Water exchange curves

The RTD curves are similar to those reported by Morrison D.J (1999) for a full scale CFD simulation with similar geometry (aspect ratio 1.1:1). He reported slight re-circulation for the downturned bellmouth or "*circular* inlet", believed to be from top to bottom. In this study the recirculation was clearly evident. This was due to more pronounced adherence of the flow to the walls of the physical model than was apparent in the CFD simulations. The resulting flow patterns were similar. Top to bottom recirculation was not noted in the physical model, possibly due to the angle of filming and observation.

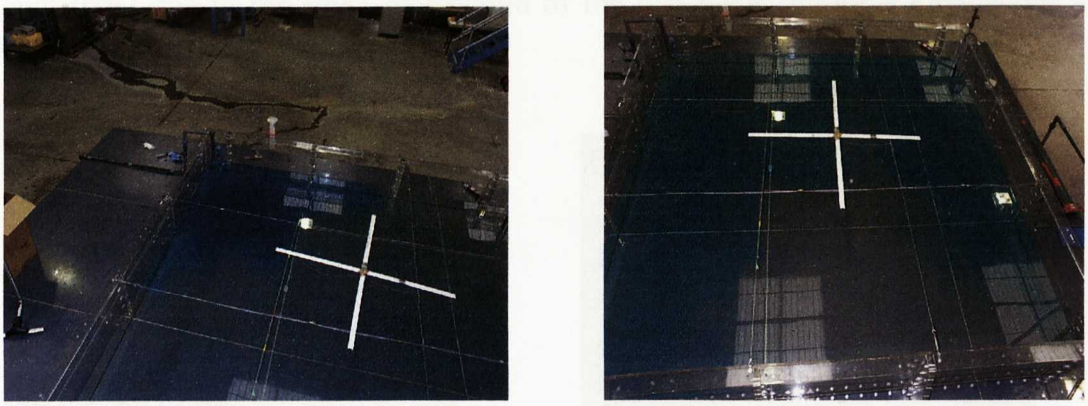


Figure 5.27 - Dye tests Series 13

Intermittent flow.
For Series 11, 12 and 13 the basic performance of the geometry did not deteriorate when operated with intermittent flow, where the inlet and outlet were operated for inlet / outlet operational durations of 0.5T.

5.3.3 Series 14: Multiple adjacent inlets: Upturned bellmouth and downturned bellmouth inlets above TWL: Outlet directly or diagonally opposite

A number of sites surveyed had multiple high level inlets. Series 12 & 13 tests were extended accordingly to assess the use of multiple inlets in these configurations.

The performance and the flow pattern established in the model was dependant upon the exact placement and proximity of the multiple inlets. Better performance was achieved when the inlets were positioned so close together that they behaved as a single inlet jet. It was apparent that the alignment and relative momentum of the inlets determined the uniformity of the inlet jet and influenced the resulting flow pattern and performance of the tank. (See Table 5.10). In general performance deteriorated when the inlets were any significant distance apart. Again the m-p model interpreted internal recirculation as plug flow.

			T_{mean}	m-p model		
Short-circuiting	CV	T (mix)	Dead Space	Dead Space	Plug Flow	CSTR
0.63 to 6.42	0.10 to 0.12	0.506 to 0.605	0 to17	-60	22	139

Table 5.10 - Series 14: Multiple inlet model performance characteristics.

More pronounced recirculation was noted on a number of the tests. Figure 5.28 below depicts a multiple inlet dye test with blue dye from the left inlet and purple from the right inlet. The general flow pattern is similar to Series 11,12 and 13, however the flow doesn't spread through the middle of the tank, but progresses around the side walls until it reached the outlet. Two recirculation cells are established, in this case reasonably symmetrical due to the equal momentum of the two inlets. Multiple circulations are established similar to those in Series 5.

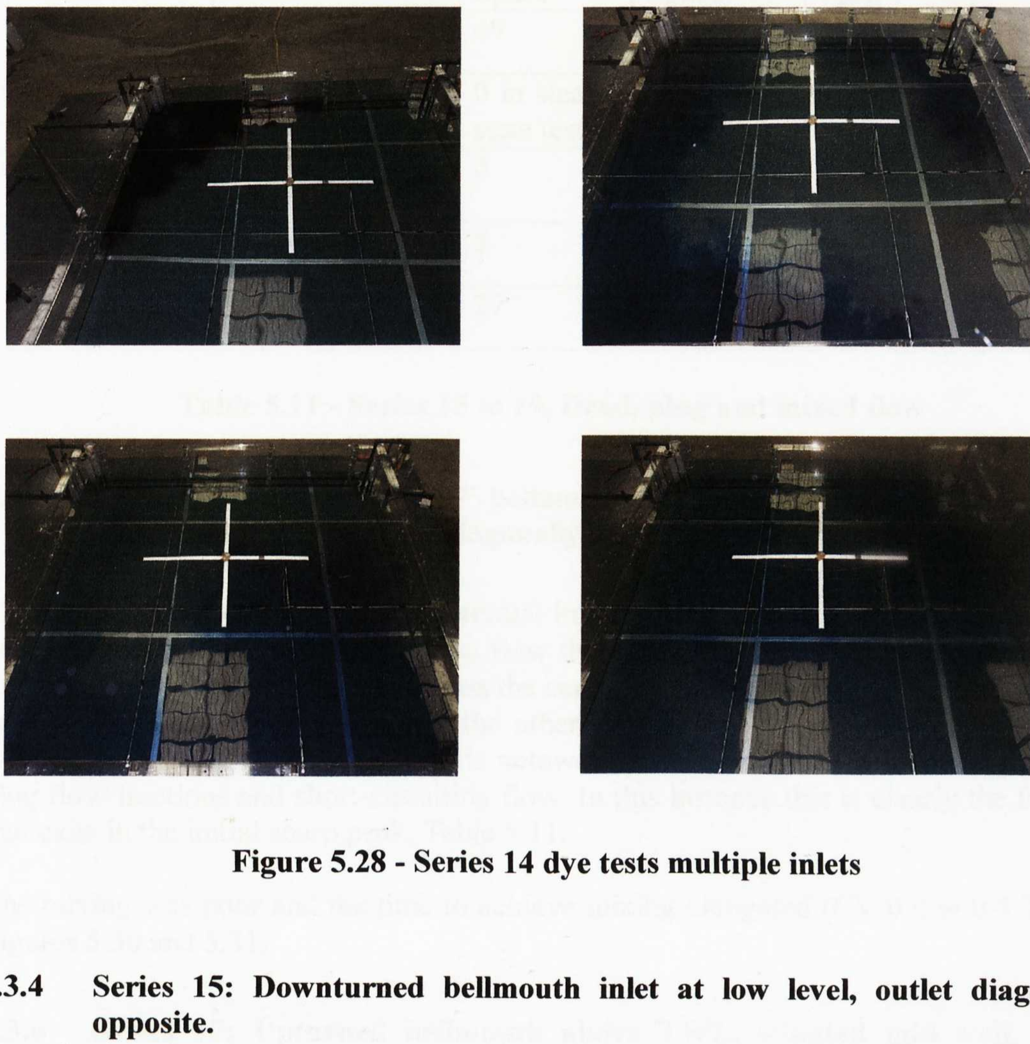


Figure 5.28 - Series 14 dye tests multiple inlets

5.3.4 Series 15: Downturned bellmouth inlet at low level, outlet diagonally opposite.

The flow pattern was similar to that established in Series 13, however there is greater flow adherence to the side walls, resulting in the propensity for the formation of a central dead area in the centre of the tank, (Table 5.11). The t mean and m-p models produced correlating values for dead volume. The time to achieve mixing was the similar to Series 13, CV 0.08 in 0.3 T, note the low CV value in comparison to the large dead volumes. In general there were no advantages of this arrangement over a downturned bellmouth above TWL. Performance was poor and corrosion of the base of the tank in the vicinity of the inlet would be expected. Hence it would not be recommended in a full-scale design.

Intermittent flow.
The performance of the geometry did not deteriorate significantly when operated with intermittent flow. A single test only was performed.

		T_{mean}	m-p model		
	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
Series 15	0	49	45	15	38
Series 16	20	0 in steady state test	-14	20	94
Series 17	1.8	0	0 – 3	6-12	89-91
Series 18	26 to 35	5	-30	2	128
Series 19	0	27	42	5	53

Table 5.11 - Series 15 to 19, Dead, plug and mixed flow

5.3.5 Series 16: Downturned 45° bellmouth above TWL, directed towards the centre of the tank, outlet diagonally opposite

This arrangement was trialed as a potential improvement on Series 13; it was proposed on the basis that it might improve the flow through the centre of the tank. During dye tests the inlet jet did spreads out across the centre of the tank, however it resulted in the potential for dead area formation in the other two corners of the tank. The percentage short-circuiting was high 20%, what is noteworthy is the correlation between predicted plug flow fractions and short-circuiting flow. In this instance this is clearly the fraction that exits in the initial sharp peak, Table 5.11.

The mixing was poor and the time to achieve mixing elongated (CV 0.4 in 0.4 T). See Figures 5.30 and 5.31.

5.3.6 Series 17: Upturned bellmouth above TWL, situated mid wall, outlet directly opposite

With the inlet situated mid wall there was still a strong tendency for flow to adhere to the side walls, with slower moving flow through the middle of the tank and again the propensity for formation of a small dead area in this zone (Table 5.11). Mixing achieved and mixing times were good (CV 0.14 in 0.25 T). The inlet flow was well dispersed and water exchange rate reasonable, Figures 5.30 & 5.31.

5.3.7 Series 18: Upturned bellmouth inlet: outlet mid wall on the same wall

This configuration did arise in one full scale plant during the survey, although the aspect ratio and outlet position were not exactly 1:1 and mid wall, respectively. The general flow pattern was similar to Series 11, however as anticipated there was significant increased short circuiting due to relative position of inlet and outlet, Table 5.11, Figure 5.30. The mixing achieved and mixing time was therefore compromised (CV 0.3 in 0.714 T). The m-p model predicted CSTR flow.

During transient dye tests where the outlet flow was greater than the inlet flow this arrangement lead to the formation of a dead area in the corner diagonally opposite the inlet.

5.3.8 Series 19: Upturned bellmouth at floor level in central position, outlet in corner

Although this arrangement did not occur during the full-scale plant survey, it was included because other investigators have evaluated similar arrangements. In steady state conditions, the inlet flow jets up to the surface and spreads out radially. The highest velocities occurring across the surface of the tank, with slower moving flow around the walls. The flow pattern was biased by the position of the outlet, resulting in a large dead area in the corner, Figure 5.29.

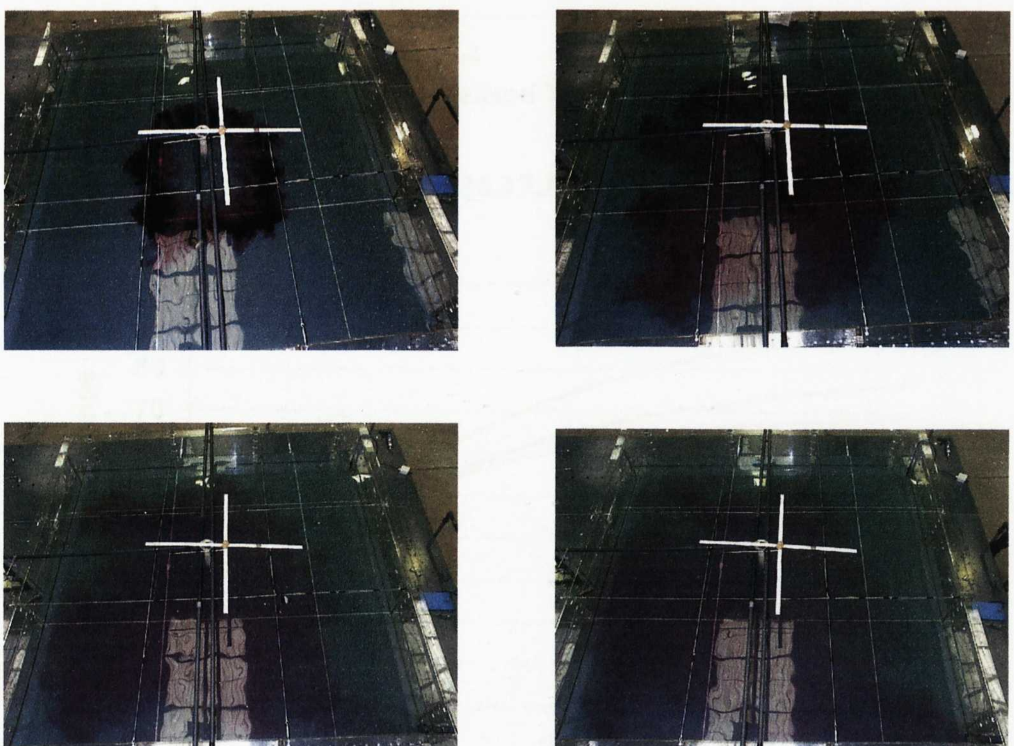


Figure 5.29 - Dye tests Series 19: Central upturned bellmouth inlet

There was some variation in the estimated dead volume, 27 to 42 % as determined by the t_{mean} and m-p models respectively. The remaining volume of the tank comprised principally mixed flow.

The time to achieve a sustainable CV was very rapid, 0.08 T and the measured CV was good at 0.15. In this instance, no internal probes were situated in the dead corner. Consequently the final calculation did not accurately represent the whole tank. RTD curves and water exchange curves are shown in Figures 5.30 and 5.31 respectively.

If applied at full scale, this design would be likely to result in greater decay of chlorine residuals, as the highest concentrations (incoming water) would be across the surface of the tank.

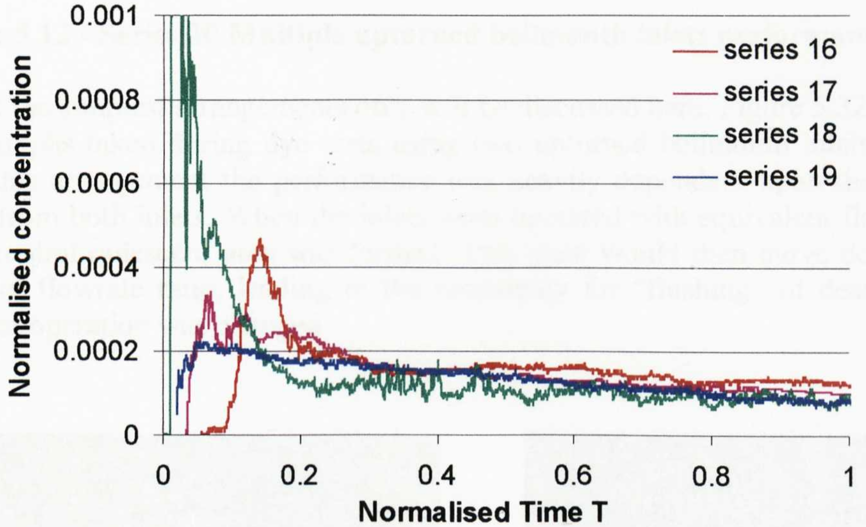


Figure 5.30 - Series 16,17,18 & 19 RTD curves

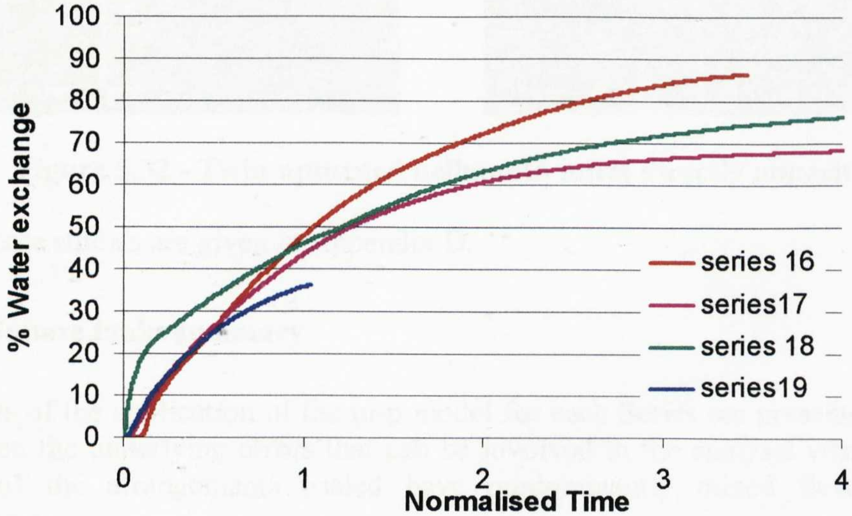


Figure 5.31 - Series 16, 17, 18 & 19 water exchange curves

5.3.9 Series 20: Multiple upturned bellmouth inlets above TWL.

A number of multiple inlet arrangements were trialed. The performance proved highly dependent upon relative inlet flowrates, momentum and position. A summary of the range of results is given in table 5.12 below.

			T_{mean} model	m-p model		
Short circuiting	CV	T mix	Dead space	Dead space	Plug flow	CSTR
0.22 to 20.44	0.084 to 0.1	0.216 to 0.42	0 to 23	-60 to -160	22 to 51	139 to 210

Table 5.12 - Series 20 Multiple upturned bellmouth inlets performance measures.

One of the simplest arrangements only will be discussed here. Figure 5.32 below, shows photographs taken during dye tests using two upturned bellmouth inlets above TWL. With this arrangement the performance was heavily dependent upon the relative inlet flows from both inlets. When the inlets were operated with equivalent flowrates then a large central quiescent area was formed. This zone would then move depending upon the inlet flowrate ratio, leading to the propensity for "flushing" of dead areas as the mode of operation was changed.

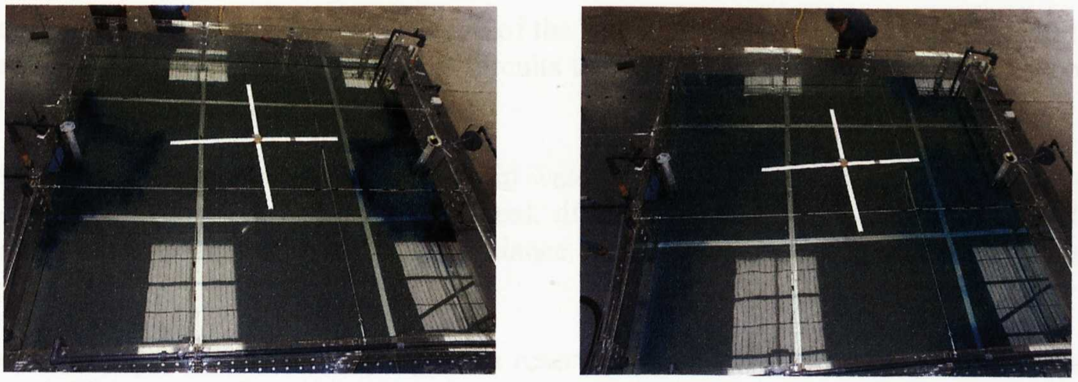


Figure 5.32 - Twin upturned bellmouth inlets directly opposite

Detailed case studies are given in Appendix D.

5.3.10 Square tanks summary

The results of the application of the m-p model for each Series are presented in Figure 5.33. Given the underlying errors that can be involved in the analysis what is clear is that all of the arrangements trialed have predominantly mixed flow or CSTR characteristics.

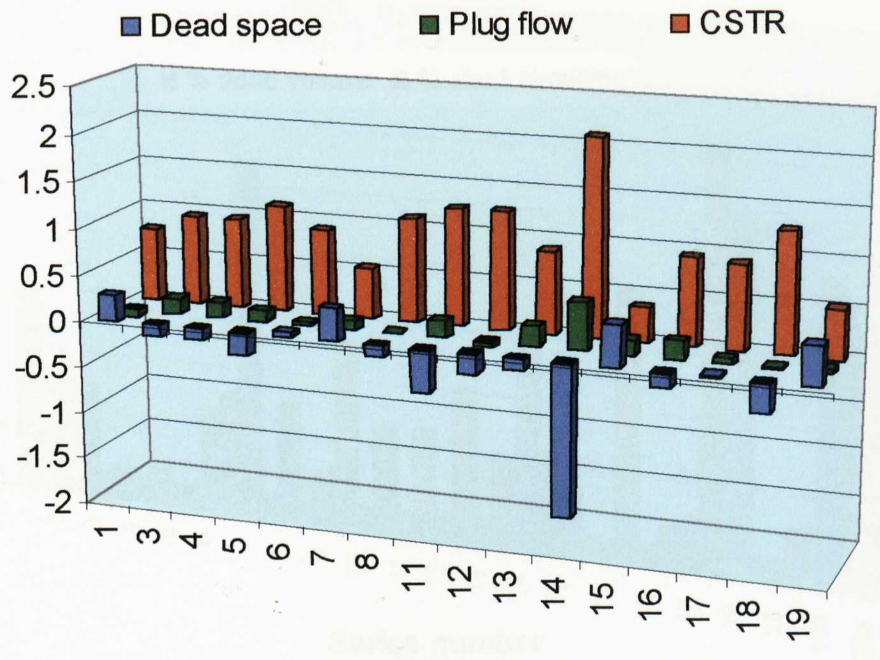


Figure 5.33 - Series 1-20: m-p model: dead space, plug flow and mixed flow fractions.

It is therefore not surprising that the majority of the evaluations in the literature assess these types of vessels as behaving like completely mixed tanks.

However, typically the smaller fractions of the flow in particular the dead space, and the fraction of the inlet flow which short circuits to the outlet are indicated in quality non-compliance issues.

Dead volumes in a reservoir can result in water quality issues such as taste and odour complaints, erratic / low chlorine residual, dirty water incidents and increased THM formation and bacteriological non-compliance. They also provide "effective" settlement zones.

Short-circuiting can be an issue where a reservoir is directly after a WTW; any short-term infringement of quality parameters at the WTW can result in compliance failures in distribution. Changes in treated water quality are more evident to the customer.

Figure 5.34 presents the average dead volumes and short-circuiting for the respective Series. From simple comparative plots such as 5.33 and 5.34 it becomes evident which Series result in better overall performance. It is important to note which arrangements were robust with respect to operational changes.

A graph of time to achieve mixing versus CV for Series 1-20 is presented in Figure 5.35. The closer to the origin a Series marker is, the better the degree of measured mixing and the faster the rate of mixing. These criteria will be important for reservoirs that are operated with intermittent flow and sites that supply industrial customers, who may be more sensitive to quality changes within the legislative limits.

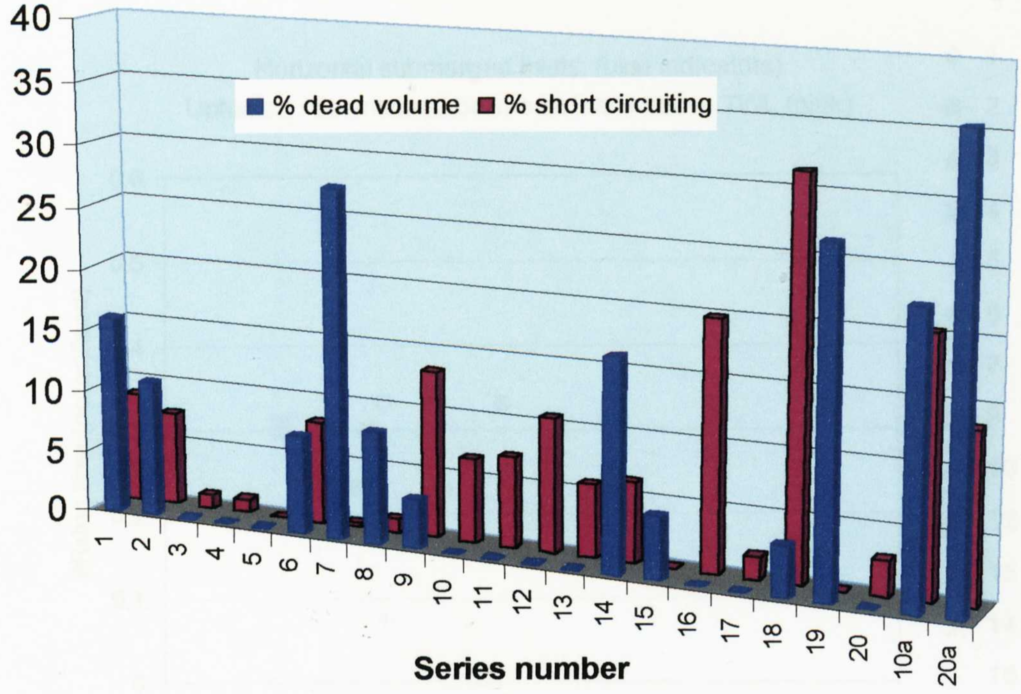


Figure 5.34 - Series 1-20: Percentage dead volume & percentage short-circuiting

Coefficient of variation was plotted against normalised mixing time, high level inlets above TWL were indicated by pink labels and horizontal submerged inlets were indicated by blue labels. Given the performance range covered by both types of inlet it was concluded that the position and nature of the inlet and outlet were also important factors in the determination of mixture quality and mixing time.

Grayman et al (2000) concluded that for square tanks mixing time was generally independent of the location and direction of the inlet, hence the use of the Okita and Oyama (1993) mixing model was appropriate and good correlations were reported. his was qualified with the statement that longer mixing times were observed when a vertical inlet was used.

During this study when the Okita and Oyama (1993) model was applied to a single geometry over a range of operational conditions and inlet diameters. Very good correlations were achieved.

On application across the range of the square tank inlet and outlet arrangements trialed during this study the correlation was negligible (R^2 =0.006).

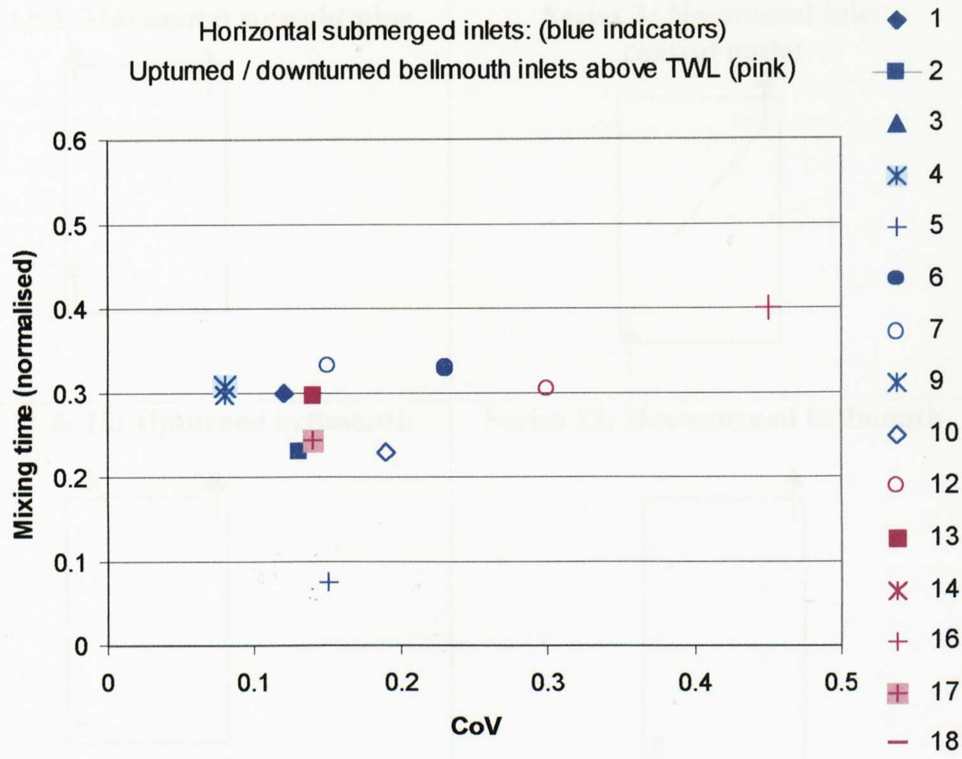


Figure 5.35 - Series 1-18: CV & Mixing time (T)

Comparison with the full scale CFD simulations conducted by Morrison (1999) at an aspect ratio of 1.1:1, for similar inlet and outlet arrangements (Series 1, 11, 13) showed that broadly similar flow visualisation results were obtained. Predicted areas where quiescent zones would be situated were the same. The CFD simulations predicted less short-circuiting along the tank walls adjacent to the inlet and improved dispersion through the centre of the tank for Series 11 and 13. As the CFD simulations were conducted with different boundary conditions to the physical modelling study this should only be expected.

5.4 Rectangular Tanks: Tanks with aspect ratios 1.4: 1 to 3.9:1

Of the tanks surveyed 25% had aspect ratios between 1.5:1 and 3.9:1. Many of the inlet and outlet arrangements were similar. Results will be presented for the most common inlet / outlet arrangements and those that resulted in the best performance from the square tank Series of tests, as described in Figure 5.36. These were Series 1, 2, 3, 11, 12, and 13 respectively.

In this section we will evaluate how the performance of a given arrangement changes with changing aspect ratio of the model. Comparisons of inlet arrangement for each aspect ratio will be summarised at the end of the section

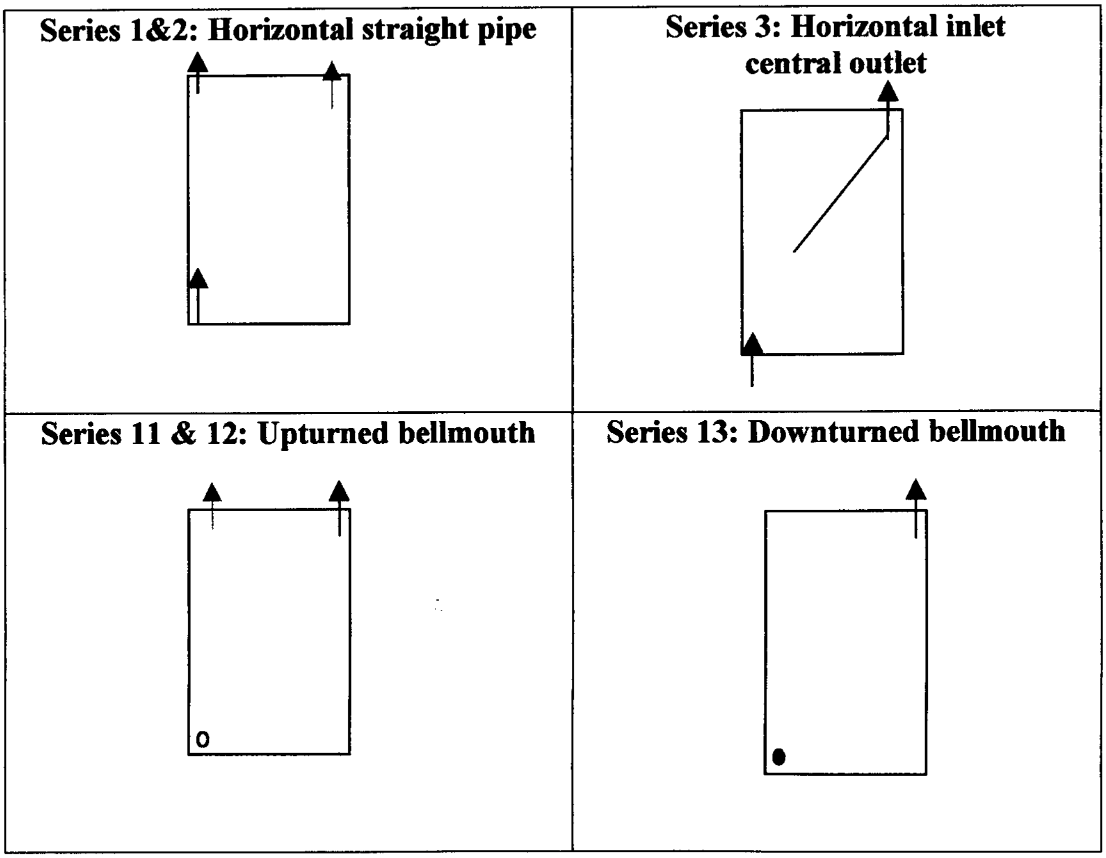


Figure 5.36 - Rectangular tank test configurations

5.5 Horizontal: Base level inlet and outlet diagonally / directly opposite

5.5.1 Aspect ratio 1.4:1

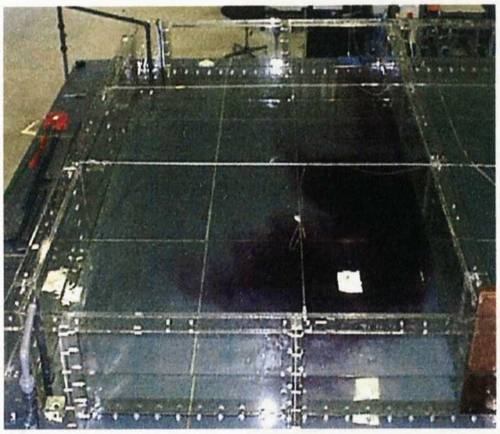
The generalised flow pattern is the same as that in the square tank tests, with a strong circumferential circulation and central dead area. Analysis showed that the estimated percentage dead volume reduced from a maximum of 40 to 22 % possibly as a function of the increase in tank length to width ratio and possibly the corresponding decrease in tank width to inlet diameter ratio, table 5.13. The remaining tank volume being mixed flow. Short-circuiting remained the same and the time taken to achieve water exchange is still long as a function of the central dead zone. However in changing the aspect ratio from 1:1 to 1.4:1 the overall performance of the arrangement improved.

5.5.2 Aspect ratio 1.78:1

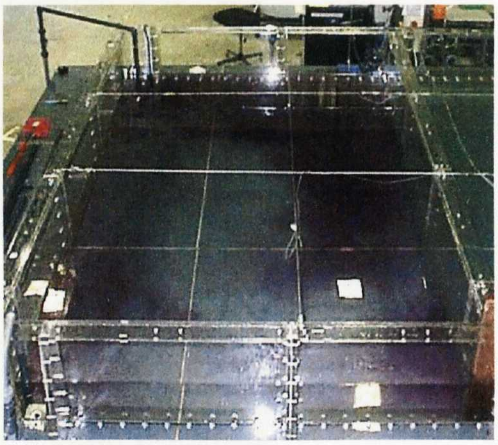
In increasing the aspect ratio to 1.78:1 the recirculating flow pattern with central dead area remains. However as the flow progresses along the length of the tank it turns before reaching the third corner, Figure 5.37 (a), resulting in a central dead area and a dead area in the corner (b). The percentage short-circuiting remains similar at 9.8 %. The measured mixing quality deteriorated while the time to achieve mixing remained similar (0.21 T). The position of the inlet was moved to different points around the circumference of the tank and repeat dye tests conducted at flowrates of 0.3 to 0.9 l/s to ascertain whether position and inlet momentum influenced the flow pattern. The variability in performance as indicated by the m-p model is a function of the changes in the flow pattern. As the predicted dead areas are reduced the plug flow fraction increases, Table 5.13.

		T_{mean}	m-p model		
Aspect ratio	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
1:1	8.9	28	28	-7	78
1.4:1	9.2	25	22	2	75
1.78	9	9	6 to 22	5 to18	72 to 74
2.4	9.8	26	5 to 21	5 to 16	72 to 77
3.9	8	0	0 to5	2 to 16	77 to 100

Table 5.13 - Series 1, 2: Aspect ratio 1.1 to 3.9:1



(a)



(b)

Figure 5.37 - Aspect ratio 1.78:1: Horizontal straight pipe inlet outlet directly opposite

Further dye tests were conducted evaluating other horizontal inlet positions to establish whether the propensity for the jet to turn was a function of exact placement and aspect ratio. Dye tests at flowrates of 0.3 and 0.9l/s were also trialed for Series 5 and 9 inlet and outlet arrangements.

During the Series 5 experiments the initial flow pattern looked the same (see Figure 5.38). However the flow begin to turn less than a third of the way across the centre of the tank, resulting in a single tank circulation. The change in aspect ratio from 1:1 to 1.78:1 has influenced the flow pattern and performance of the inlet and outlet arrangement significantly.

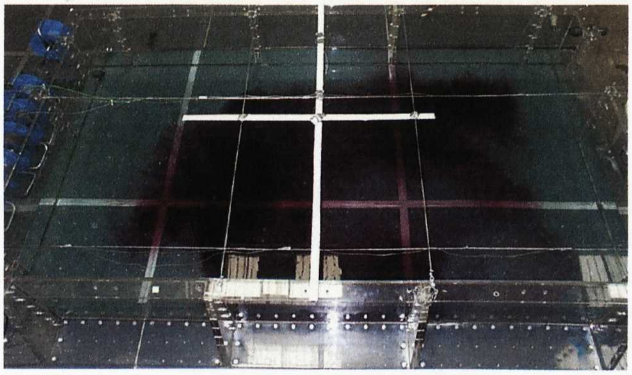


Figure 5.38 - Series 5, tank aspect ratio 1.78:1 inlet flowrate 0.9l/s.

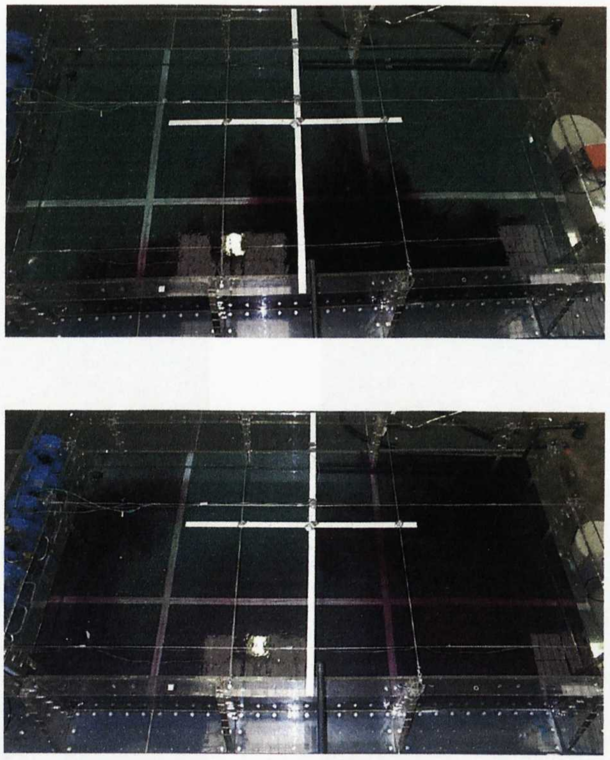


Figure 5.39 - Series 9: Aspect ratio 1.78:1

During the Series 9 experiments the inlet was placed midwall, parallel to the length of the tank, Figure 5.39. In contrast to the Series 9 experiments conducted at aspect ratio 1:1, the inlet jet does not traverse across the centre of the tank but splits and forms two circulations following the side walls. Both jets then return through the centre of the tank, resulting in twin circulations. The same flow pattern was evident at inlet flowrates of 0.3 and 0.9 l/s. In contrast, when the inlet jet was situated mid wall injecting parallel to the tank length, the inlet jet did not split but progressed through the middle of the tank towards the end wall, resulting in a large dominant circulation in two thirds of the tank and a secondary smaller recirculation cell. It was evident that the performance was a function not only of relative position of inlet and outlet but also whether the inlet jet was parallel to the longest or shortest side.

5.5.3 Aspect ratio 2.3:1

As the aspect ratio increases to 2.1:1 the inlet jet turns in a shorter distance along the third wall (Figure 5.40). At a ratio of 2.5:1 the flow pattern is no longer a single re-circulation, but resembles a figure of eight (Figure 5.41). The dominant circulation induces a secondary circulation in the other half of the tank. For each aspect ratio the flow pattern was consistent irrespective of inlet flowrate 0.3 to 0.9l/s. Between 2.1:1 and 2.5:1 the flow pattern goes through a transient between a single circulation pattern and a figure of eight. The transient flow is reflected by the variability in the m-p model predictions.

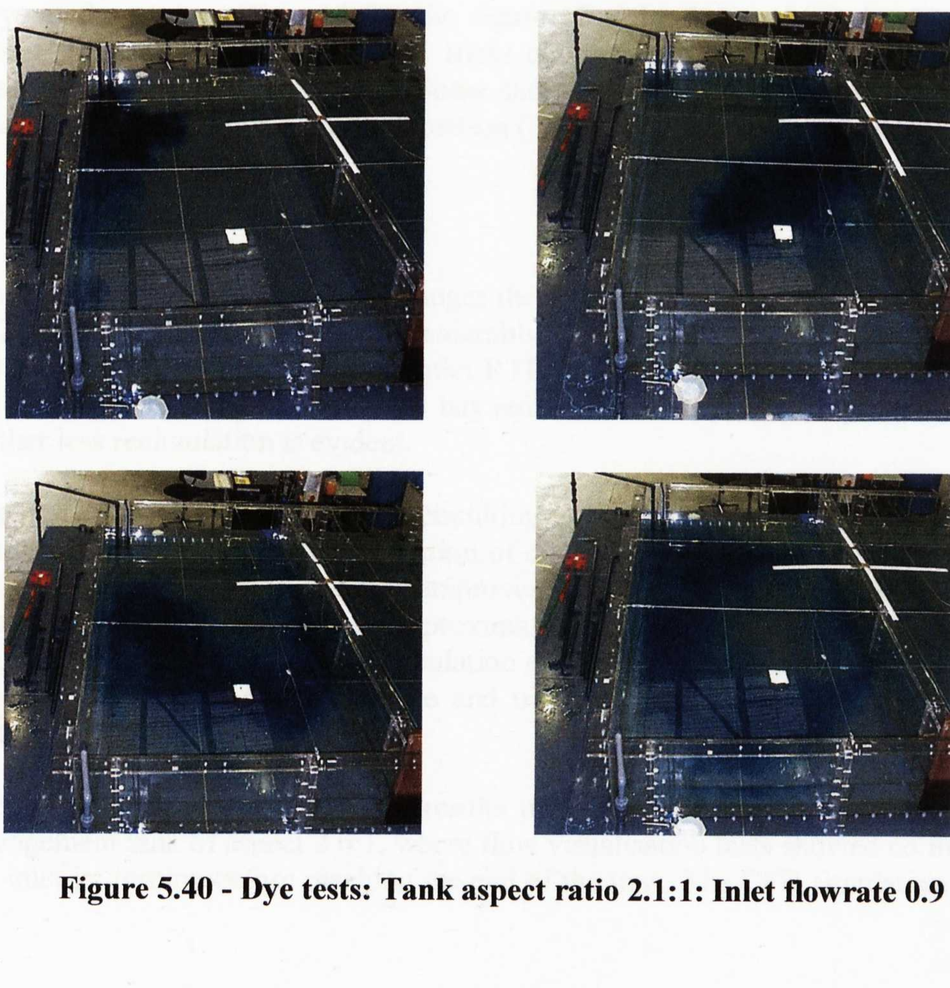


Figure 5.40 - Dye tests: Tank aspect ratio 2.1:1: Inlet flowrate 0.9 l/s

Figure 5.41 - Dye Tests: Tank Aspect ratio 2.5:1: inlet flowrate 0.9 l/s

5.5.4 Aspect ratio 3.9:1

Beyond the aspect ratio of 2.5:1 the figure of eight flow pattern dominates. As the aspect ratio increases beyond 3.7:1 triple circulation starts to occur. This was rarely observed as a stable flow pattern. Some short-circuiting occurs. The tank has minimal dead areas (<8 %) some plug flow fraction (2 to16 %) but is mostly well mixed.

5.5.5 Comparative results

It is clear that as the aspect ratio changes the flow pattern and performance of a Series 1 or 2 type configuration changes considerably. The RTD curves in Figure 5.42 show that the multiple recirculations in the outlet RTD are reduced as the aspect ratio increases. At 2.3:1 the number of circulations has reduced to 3 and as the aspect ratio increases further less recirculation is evident.

The percentage of inlet flow short-circuiting to the outlet remains similar although the time to the outlet changes as a function of distance and expansion of the inlet jet. The estimated dead volume in the tank improves steadily as the aspect ratio increases then deteriorates at an aspect ratio of approximately 2.3:1 as the flow pattern can be in the transient phase between a single circulation and a figure of eight, Figure 5.43. In general the time to achieve water exchange and trace recovery improves as the aspect ratio increases, Figure 5.43.

These results contrast to the CFD results presented by Morrison, 1999, for a similar arrangement tank of aspect 2.0:1, where flow visualisation tests showed no indication of the inlet jet turning before reaching the end of the tank. The CFD simulation resulted in a very similar flow pattern being established to the results presented for the same inlet - outlet arrangement with aspect ratio 1.1:1. Yeung et al, 1997 reported double and triple circulations being established in a tank of aspect ratio 3.4:1, during a physical modelling study.

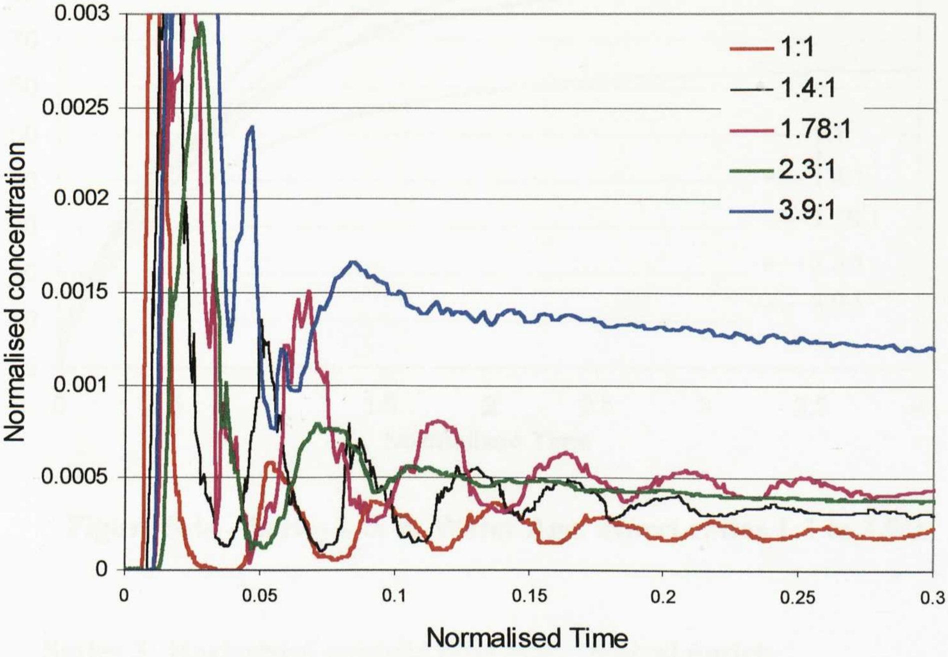


Figure 5.42 - Series 1&2 RTD curves: Aspect ratio 1:1 to 3.9:1

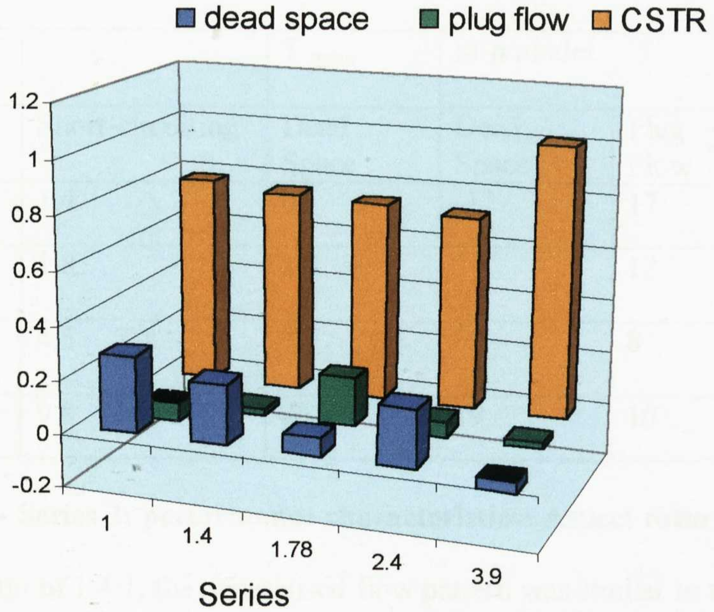


Figure 5.43 - Series 1&2: m-p model: aspect ratios 1.1 to 3.9:1

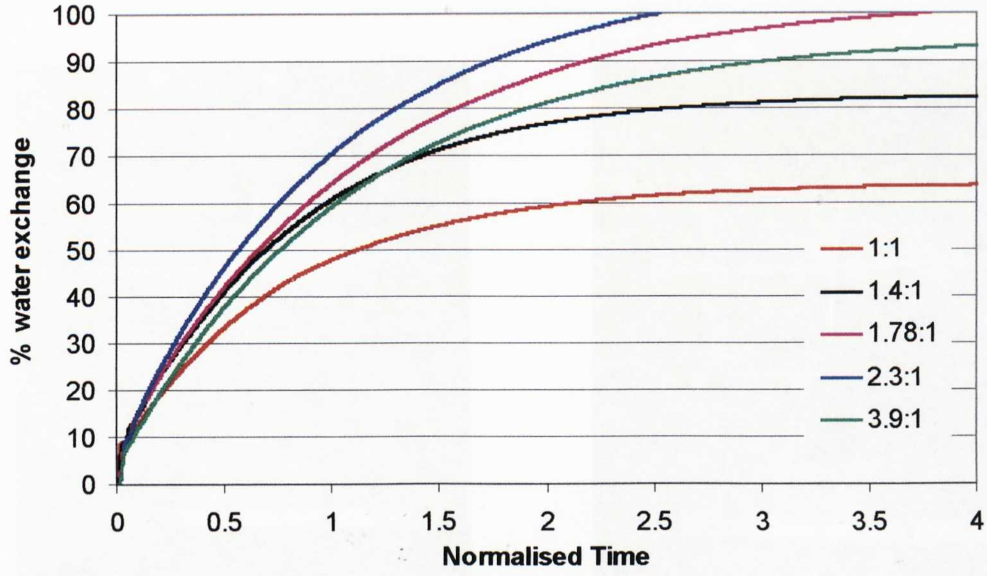


Figure 5.44 - Series 1 & 2: Water Age, aspect ratios 1:1 to 3.9:1

5.5.6 Series 3: Horizontal straight pipe inlet: central outlet:

The Series 3 inlet and outlet arrangement resulted in very good overall performance for the square tank geometry. The performance was assessed changing the aspect ratio from 1:1 through to 2.3:1 (Table 5.14)

		T_{mean}	m-p model		
Aspect ratio	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
1:1	1.4	0	-12	17	95
1.4:1	1.8	1.2	1	12	86
1.78	4.5	7.7	5	8	85
2.4	9.8	26.	19	10	70

Table 5.14 - Series 3: performance characteristics: Aspect ratio 1:1 to 2.4:1

For an aspect ratio of 1.4:1, the generalised flow pattern was similar to that achieved for the square geometry. However there was a tendency for short-circuiting on the first circulation. As the aspect ratio increased to 1.78:1 the flow turns part of the way down the longest wall on the first circulation, short-circuiting past the central outlet, resulting in similar circulation patterns, to that established with Series 1&2 at the same aspect ratio, Figure 5.45

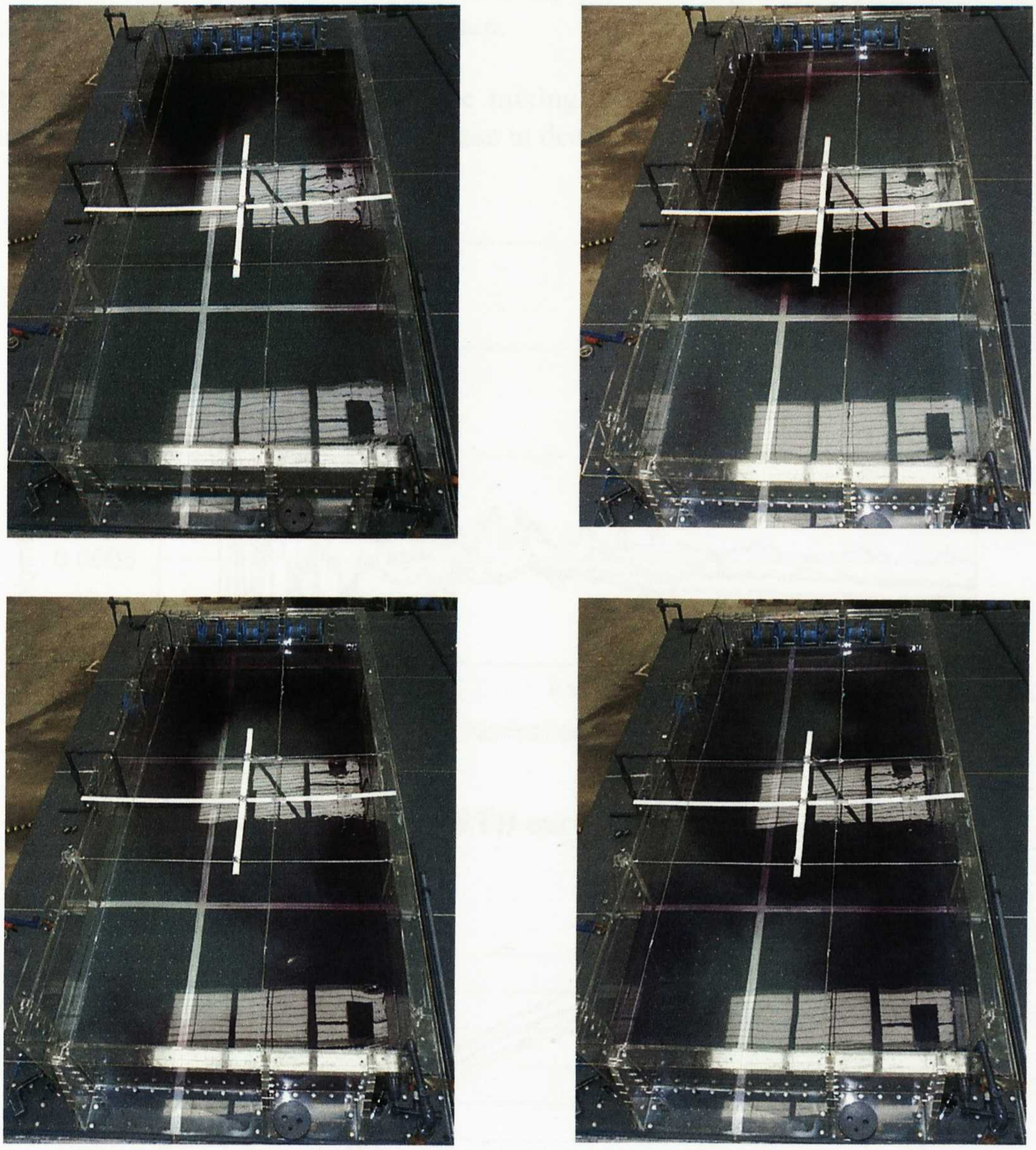


Figure 5.45 - Dye tests: Series 3: Aspect ratio 2.3:1

A number of inlet positions parallel with the tank walls were trialed to assess whether the multiple circulations were a function of placement of the inlet. However similar multiple circulations were established.

Analysis of the RTD curves, Figure 5.46, shows that as the aspect ratio increases the percentage short circuiting increases until at an aspect ratio of 2.3:1 multiple recirculations are firmly established. The flow turns directly after the second bend and turns into the centre, resulting in a figure of eight flow pattern.

Hence as the aspect ratio increases, the flow turns before reaching the end of the tank resulting in the formation of dead areas. As a result the time to achieve water exchange deteriorates Figure 5.47. The methods used to characterise the dead volume produce consistent results, the m-p model consistently predicts a significant plug flow fraction in the tank, due to the internal flow pattern.

It is notable that the time to achieve mixing is reduced but the final mixture quality deteriorates as a function of the increase in dead area.

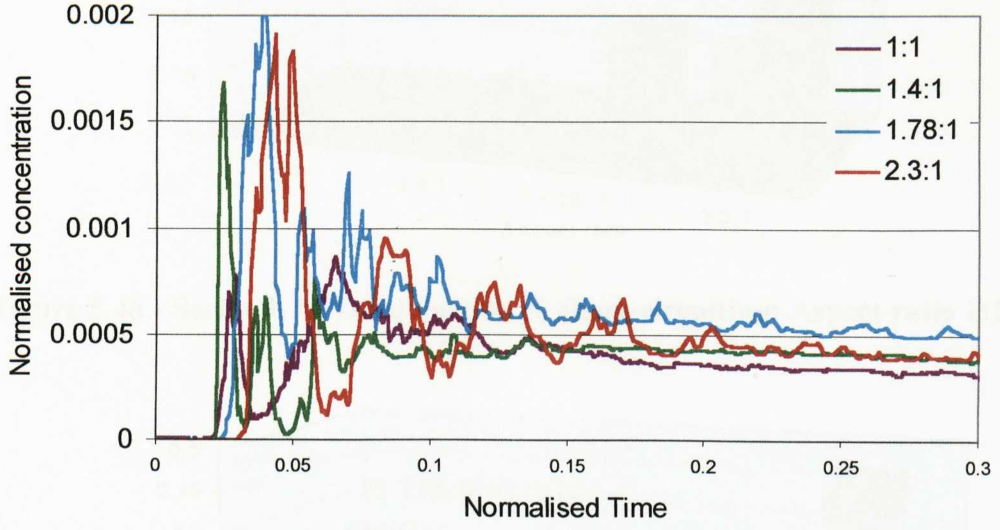


Figure 5.46 - Series 3: RTD curves: aspect ratio 1:1 to 2.3:1

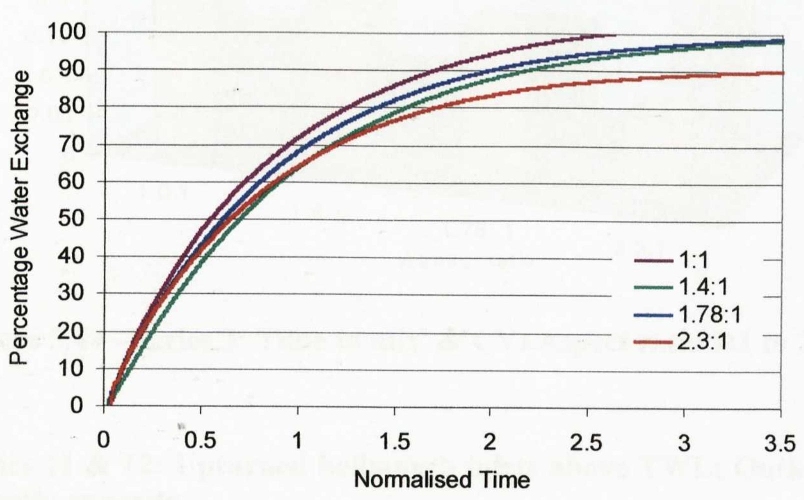


Figure 5.47 - Series 3: Water exchange curves: Aspect ratio 1:1 to 2.3:1

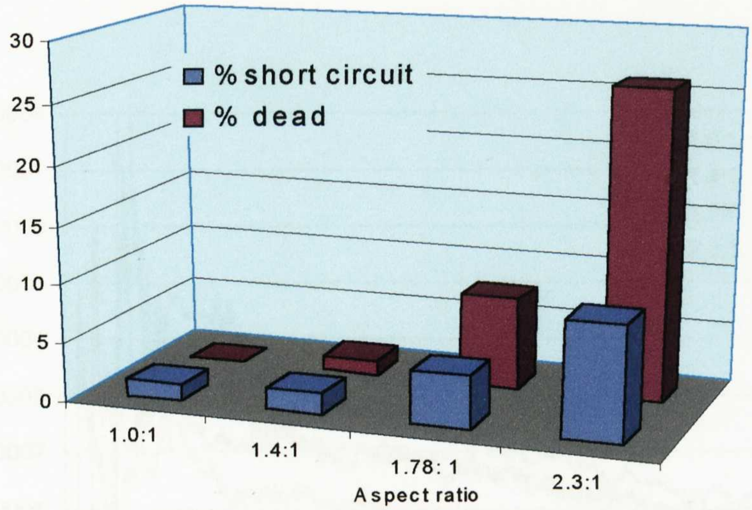


Figure 5.48 - Series 3: % Dead volume & short-circuiting: Aspect ratio 1:1 to 2.3:1

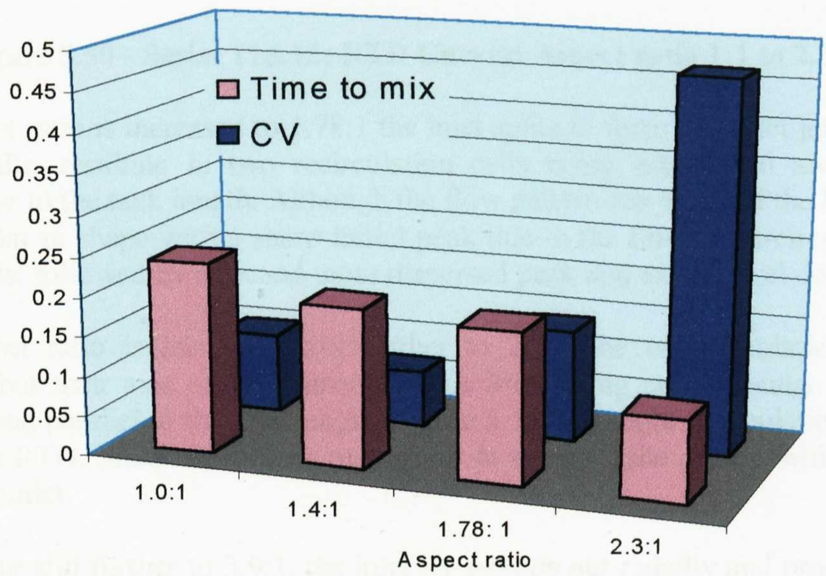


Figure 5.49 - Series 3: Time to mix & CV: Aspect ratio 1:1 to 2.3:1

5.5.7 Series 11 & 12: Upturned bellmouth inlets above TWL: Outlet diagonally directly opposite

At an aspect ratio of 1.4:1 the flow pattern is similar to that of the square tank with flow initially spreading out radially from the inlet. There is in a sharp initial peak due to the flow short-circuiting down the side walls, followed by a second more dispersed peak and an exponential decay (See Figure 5.50). This is due to the fastest flow progressing down the side walls. Flow visualisation tests indicated a small dead area in the centre of the tank.

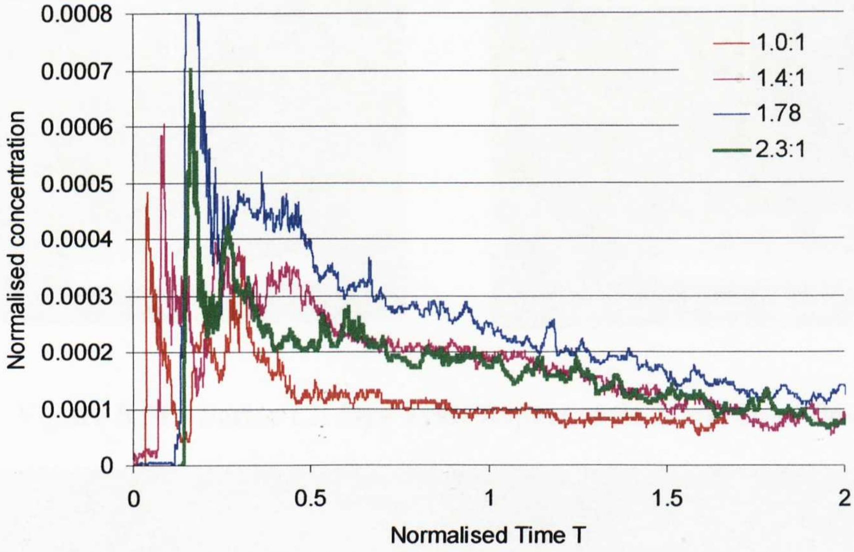


Figure 5.50 - Series 11&12: RTD Curves: Aspect ratio 1:1 to 2.3:1

As the aspect ratio is increased to 1.78:1 the inlet splits to form two inlet jets following the side walls, resulting in two recirculation cells being established about an axis perpendicular to the tank length. Although the flow pattern has changed the RTD curves remain similar in shape with a sharp initial peak due to the flow short-circuiting down the side walls, followed by a second more dispersed peak and exponential decay.

As the aspect ratio is increased still further to 2.3:1 the two circulation cells are maintained but their axis of symmetry changes from being perpendicular to the tank length to being parallel to the tank length, Figure 5.51 and slight recirculation is seen in the resulting RTD. Small dead areas may occur in the opposite corner, which does not contain the outlet.

On increasing still further to 3.9:1, the inlet jet spreads out radially and progresses in a plug flow manner down the tank and recirculation patterns are eliminated. Small dead areas may occur in the opposite corner that does not contain the outlet.

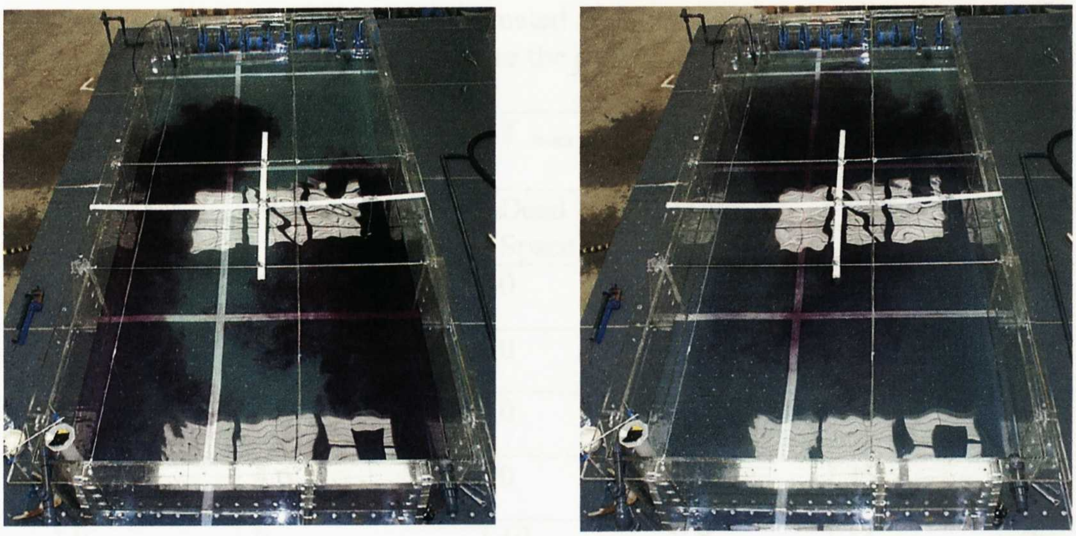


Figure 5.51 - Series 12; Dye Test: Aspect ratio 2.3:1: Inlet flow 0.9l/s

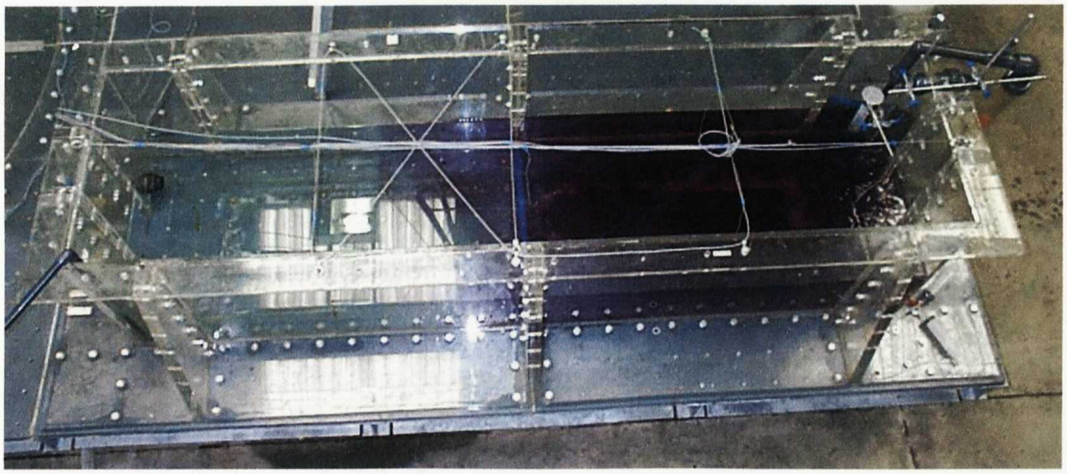


Figure 5.52 - Series 11: Aspect ratio 3.9:1: Inlet flow 0.45 l/s, pipe diameter 12.7 mm

What is notable is that although the flow pattern in the tank changes significantly with changing aspect ratio the performance is relatively robust and was not effected during the intermittent flow tests conducted. The general shape of the RTD curves remains similar regardless of the aspect ratio, with a slight increase in evident re-circulation at an aspect ratio of 2.3:1. In all cases the water exchange was improved over the 1:1 aspect ratio, figure 5.52. The performance deteriorated at 3.9:1 due to the tendency for formation of a dead area in one corner.

The time to achieve mixing was variable as one might anticipate with such transient phases in flow pattern. The percentage short-circuiting was between 4 and 12 %

between 1:1 and 2.8:1 and was eliminated at 3.9:1. The estimated dead volumes were negligible until aspect ratio 3.9:1 where the dead volume increased to 10%. Table 5.15.

		T_{mean}	m-p model		
Aspect ratio	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
1:1	6.9	0	-44	18	125
1.4:1	6.8	0	4	-5	95
1.78	12.	0	-28	25	102
2.4	4.6	0	-68	25	142
3.9	0	10	9.8	14	75

Table 5.15 - Series 11 & 12: performance characteristics

This change in flow pattern with aspect ratio beyond 1.48:1 was not evident in the CFD simulations presented by Morrison (1999), however this may be attributable to greater initial adhesion of the flow to the side walls in the physical model.

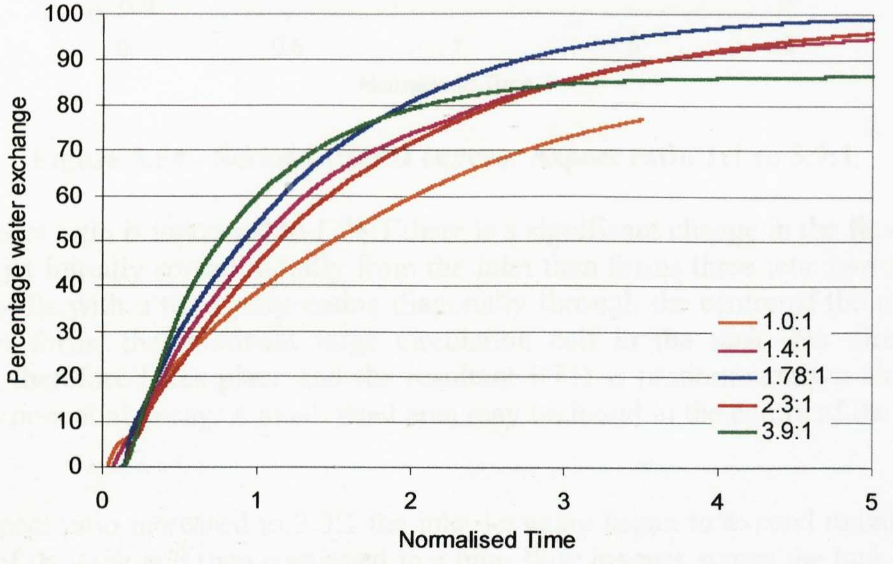


Figure 5.53 - Series 11 & 12: Water Exchange: Aspect ratios 1:1 to 3.9:1

5.5.8 Series 13: Downturned bellmouth inlets above TWL: Outlet diagonally / directly opposite

At an aspect ratio of 1.4:1 the flow pattern established is very similar to that in Series 11&12 at this aspect ratio. The RTD shows a similar initial peak due to flow short-circuiting down the side walls. Followed by a second more dispersed peak and an exponential decay. There can be small dead area in the centre of the tank.

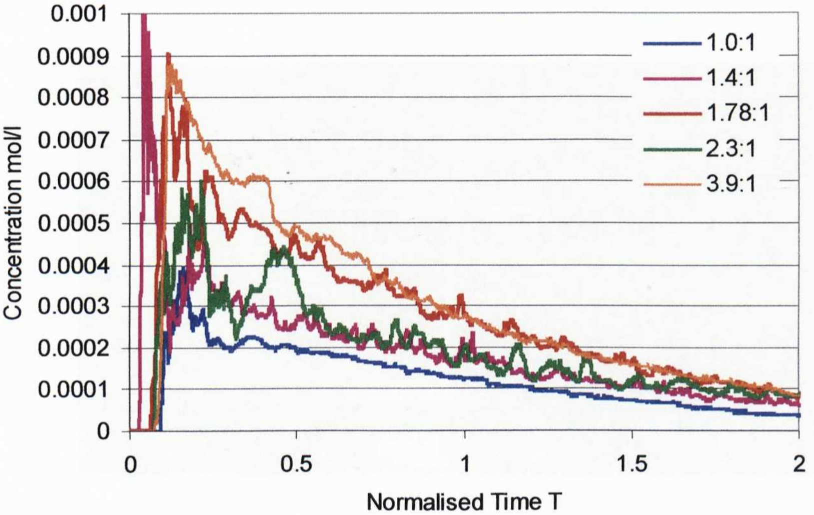


Figure 5.54 - Series 13:RTD curves: Aspect ratio 1:1 to 3.9:1

As the aspect ratio is increased to 1.78:1 there is a significant change in the flow pattern. The inlet jet initially spread radially from the inlet then forms three jets: two following the side walls with a third progressing diagonally through the centre of the tank. The central jet forms the dominant large circulation cell in the tank. No direct short-circuiting therefore takes place and the resultant RTD is predominantly a single peak with an exponential decay. A small dead area may be found in the centre of the tank.

As the aspect ratio increased to 2.3:1 the inlet jet again began to expand radially across the base of the tank and then continued in a plug flow manner across the tank length to the outlet, resulting in no direct short-circuiting and no dead areas.

The plug flow performance was maintained at an aspect ratio of 3.9:1. However small dead areas may occur in the opposite corner that does not contain the outlet.

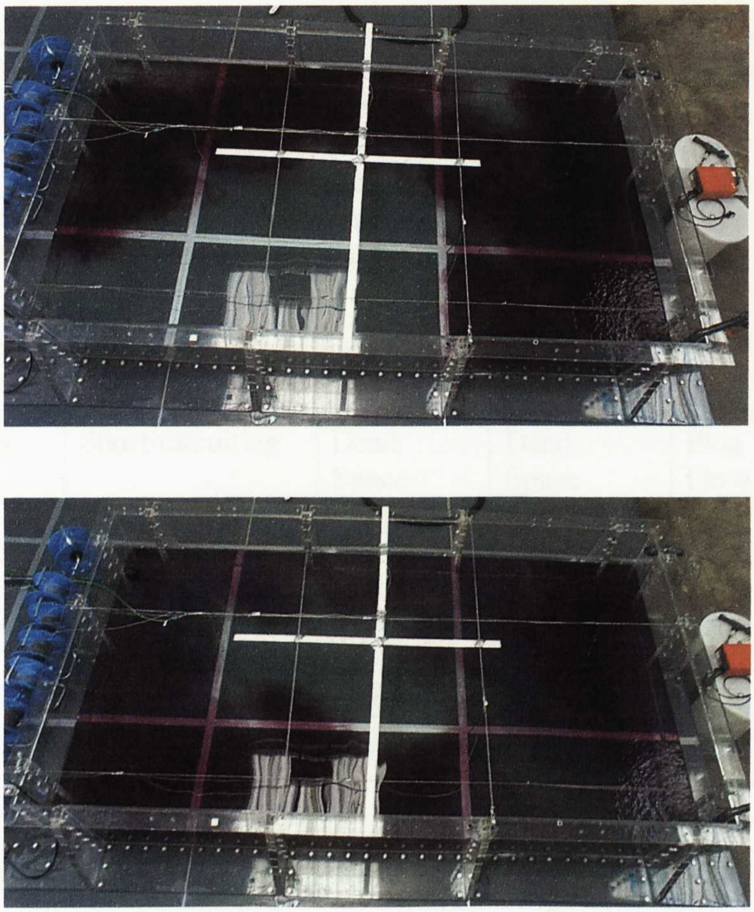


Figure 5.55 - Series 13: Dye tests: Aspect ratio 1.78:1, inlet flow 0.9 l/s

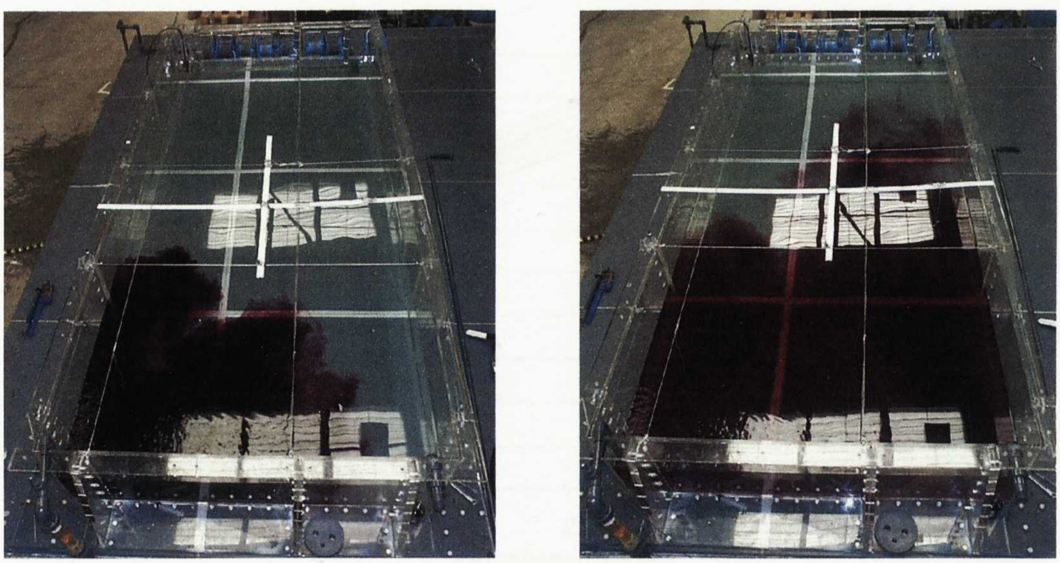


Figure 5.56 - Series 13: Dye test: Aspect ratio 2.3:1: Inlet flow 0.9 l/s.

It is apparent that the flow pattern changes as a function of the aspect ratio of the tank. However the RTD curves remained very similar and the performance of the tank did not deteriorate or change significantly according to m-p model and t_{mean} models. The fraction of mixed and plug flow remained pretty constant. Short-circuiting was variable, however some of these differences may be a function of the exact placement of the inlet pipework relative to the side of the tank. The performance also remained constant during the limited intermittent flow tests undertaken.

		T_{mean}	m-p model		
Aspect ratio	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
1:1	0	0.02	-10	21	89
1.4:1	11.	1.8	-3	12	90
1.78	13.	2.1	0	13	86
2.8	0	-2.6	-13	18	95
3.9	0	3.	0	16	84

Table 5.16 - Series 13: Flow characteristics: aspect ratio 1 to 3.9:1

At all geometries the water exchange remained good and dead volumes were minimised.

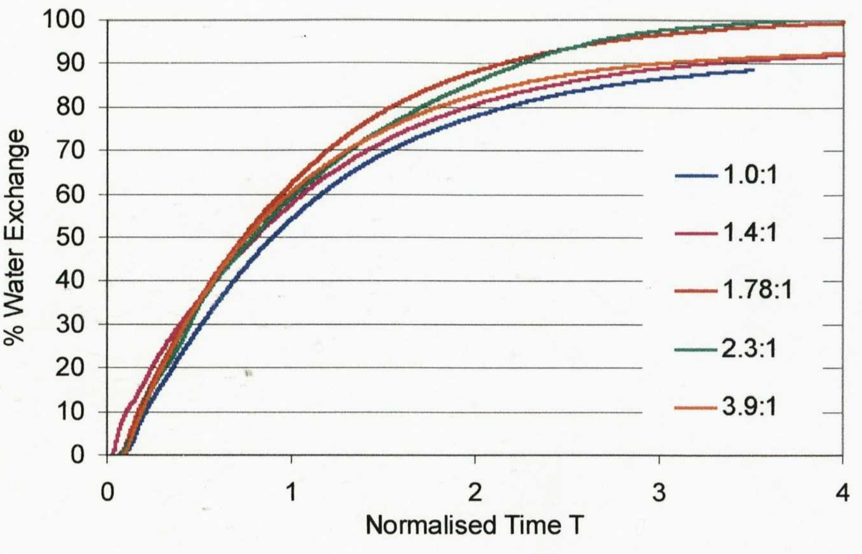


Figure 5.57 - Series 13: Water exchange: Aspect ratio 1.1 to 3.9:1

5.5.9 Comparison of Series for individual aspect ratios

For each aspect ratio the performance of each Series was compared and the results are presented in order of performance in the "Design Guide" document, Appendix D.

Figure 5.58 shows the percentage water age curves for Series 1 & 2, 3, 11 & 12, and 13 for aspect ratios of 1:1, 1.4:1 1.78:1 and 2.3:1 respectively. The curves indicate how the relative performance of each arrangement changes as a function of aspect ratio. As the aspect ratio increases from 1:1 through to 1.78:1 the difference in performance in terms percentage water age for each Series is reduced. When the aspect ratio reaches 2.3:1 the difference increases as a function of the significant changes in flow pattern already discussed. At an aspect ratio of 3.9:1 the flow patterns have stabilised and the difference in performance between Series 1 /2, 1/12 and 13 are again reduced.

In summary, from the inlet and outlet arrangements trialed during the square and rectangular tank studies, the performance of the arrangement in terms of dead volumes, short-circuiting, mixing achieved, time to achieve mixing and time to achieve complete water exchange has proved to be dependant upon the following variables:

- Aspect ratio of the tank,
- The specific inlet and outlet arrangement
- The operation of the tank (i.e.: level, inlet and outlet flowrates and pipe diameters).

When applying modelling results to full-scale plant design it is important to determine what implications the future operation of the full-scale asset may have on robustness of the design performance and hence water quality. In addition one should apply caution in the application of an inlet / outlet arrangement at aspect ratios or operational regimes which are beyond the scope of those detailed by the investigator.

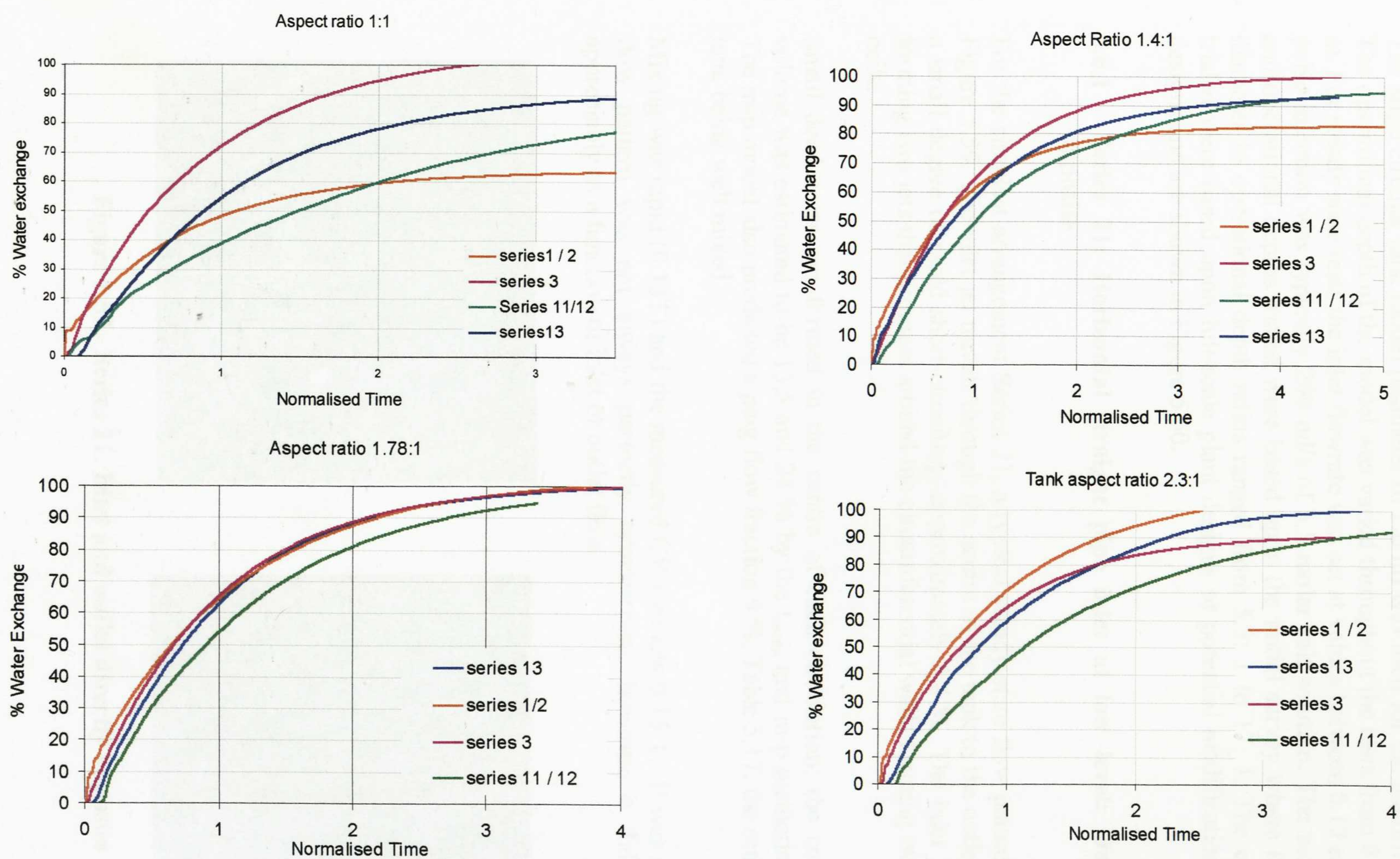


Figure 5.58 - Comparison of percentage water exchange curves: Tank aspect ratios 1:1 to 2.3:1

5.6 Circular Tanks: Single compartment

The large circular tank model (diameter of 2.6 m) was used for the majority of the tests. The operational depth of the model was varied throughout the tests from 0.242 and 0.36 m. For steady state tests the inlet flowrate was set at values between 0.12 and 0.9 l/s and pulse injection was typically 200 ml/s of 5.5 molar salt solution. The model diameter and operational depths trialed were based upon the initial survey where full-scale tank diameter to operational depth ratios ranged from 5.3: 1 to 17: 1. The configurations trialed were based upon full-scale plant designs or potential modifications to existing designs and are shown in Figure 5.60.

5.6.1 Series 21: Horizontal straight pipe inlet at low level: Outlet directly opposite

For the simplest arrangement Series 21, a typical steady state flow pattern is shown in Figure 5.59. The inlet jet travels through the centre of the tank to the outlet, resulting in a small degree of rapid short-circuiting, approximately 3.4 %. The inlet jet then splits forming two jets that progress around the circumferential walls forming twin circulation cells.

Small dead areas are formed in the centre of each circulation; the combined dead volume was estimated to be 13.5 and 24 % by the t_{mean} and m-p methods respectively. The m-p model also predicted a plug flow fraction 9 %, Table 5.17, the remainder of the tank being well mixed.

Mixing was rapid (0.13T) and the measured CV was low 0.15 T. It was noted that the flow pattern was not always perfectly symmetrical, however it did not change appreciably as a function of inlet or outlet flow.

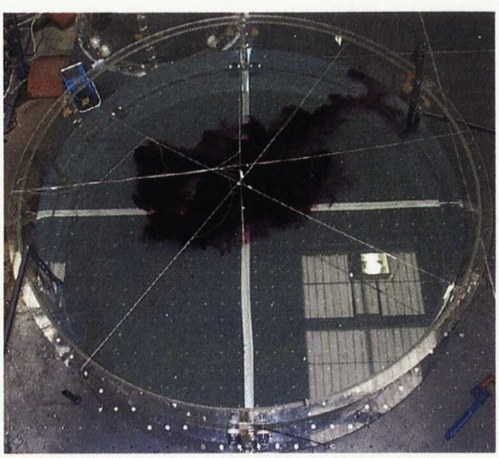
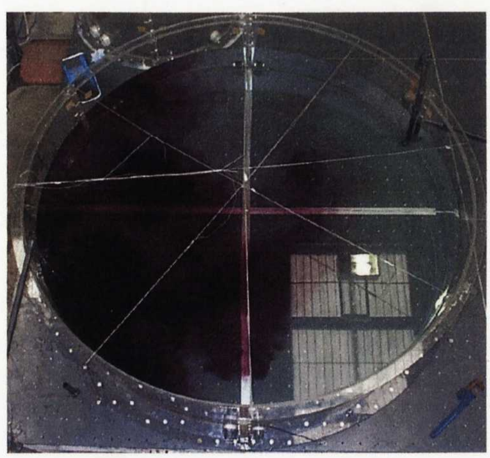



Figure 5.59 - Series 21: Inlet and outlet directly opposite

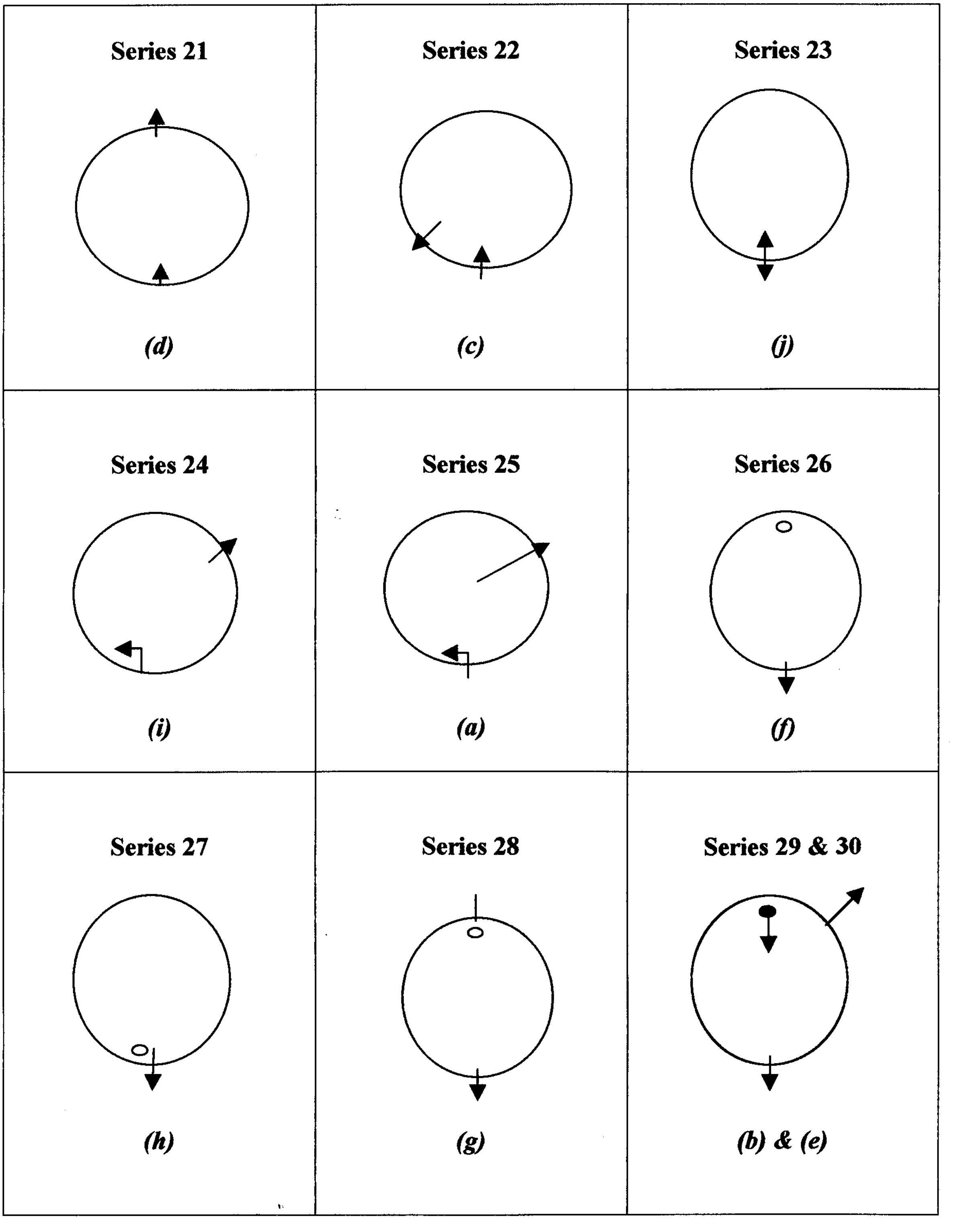


Figure 5.60 - Circular single compartment tanks

A typical RTD curve, Figure 5.61, shows that there is an initial short-circuiting peak then an exponential decay. There was no evidence of pronounced re-circulation in the tank.

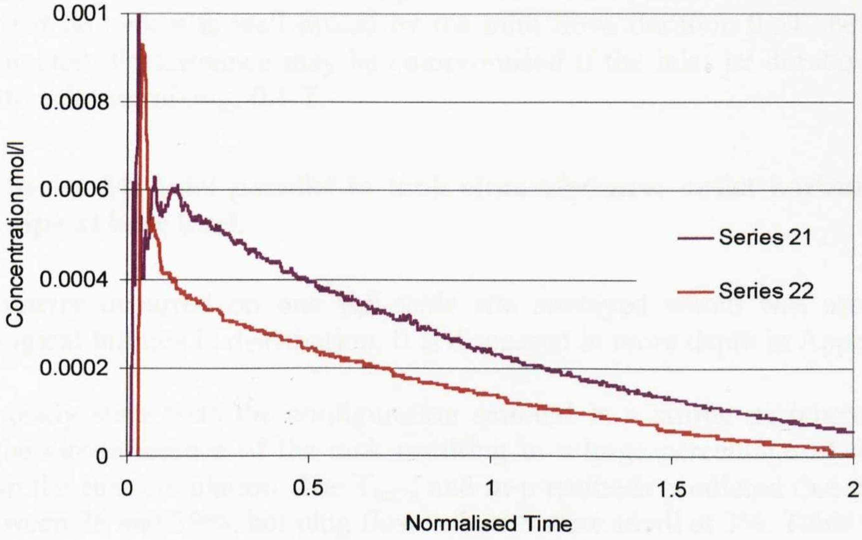


Figure 5.61 - Series 21 & 22 RTD curves

This general arrangement has been evaluated by a number of authors

5.6.2 Series 22: Inlet and outlet not directly opposite

These tests were a slight modification on the Series 21 tests, and similar geometries were encountered during the full-scale plant survey. The same general flow pattern was observed for steady state conditions and the estimated dead volume were reduced to between 0 and 7 %. The short-circuiting became negligible by the increased flow path to the outlet. As the basic flow pattern remained the same the same fraction of plug flow was predicted 9% (Table 5.15).

During transient dye tests the flow pattern was severely biased by the position of the outlet. While mixing and time to achieve water exchange was good during steady state tests the performance of the arrangement deteriorated during transient and intermittent flow tests indicating that the performance is intrinsically less stable than Series 21.

5.6.3 Series 23: Inlet and outlet adjacent (or common main)

During steady state trials of the geometry as a separate inlet, outlet arrangement the flow patterns and RTD curves were similar to those observed for Series 21, with a small degree of short-circuiting directly to the outlet.

Again during transient tests where the outlet flow was increased the flow pattern in the tank was biased by the outlet position and increased short-circuiting and poorer mixing occurred.

The results of the intermittent flow tests indicated that performance of the arrangement was similar to that achieved with steady state flow. Analysis of the internal tank probes showed that he tank was well mixed by the inlet flow, duration 0.5T, before the inlet was terminated. Performance may be compromised if the inlet jet duration is less than the time to achieve mixing, 0.1 T.

5.6.4 Series 24: Inlet parallel to tank circumference: outlet horizontal straight pipe at base level.

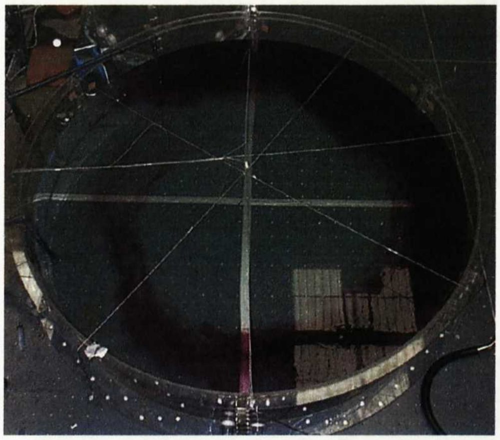
This geometry occurred on one full-scale site surveyed which was associated with bacteriological failures in distribution. It is discussed in more depth in Appendix C.

During steady state tests the configuration resulted in a strong peripheral circulation around the circumference of the tank resulting in a large percentage of the inlet flow exiting on the first circulation. The T_{mean} and m-p methods predicted that dead volumes were between 26 and 39%, but plug flow volumes were small at 3%, Table 5.17.

		T_{mean}	m-p model		
Series	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
21	3.4	13.5	24	9	66
22	0.1	7	-3	9	93
24	11.4	39.2	26	3	69
25	0	0.3 to 15	15	3	80

Table 5.17 - Series 21 to 15: performance characteristics

This resulted in extremely poor mixing, CV of 0.8 in 0.39 T and a correspondingly long time to achieve complete water exchange. See Figures 5.63 and 5.65.



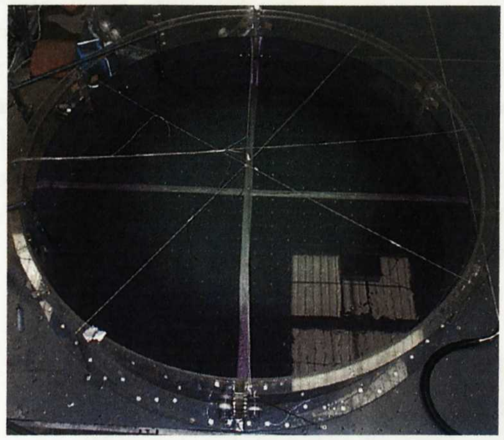


Figure 5.62 - Series 24 Dye tests: Inlet & outlet flow 0.9l/s

The RTD curve, Figure 5.63, shows that there is marked re-circulation in the tank, short-circuiting is pronounced, 11.4 % of the inlet flow exiting on the first circulation. The circulation times are similar to those reported by Grayman (1996), t_{circ} 0.04, for a full scale and physical modelling study of a similar geometry. RTD data was not presented.

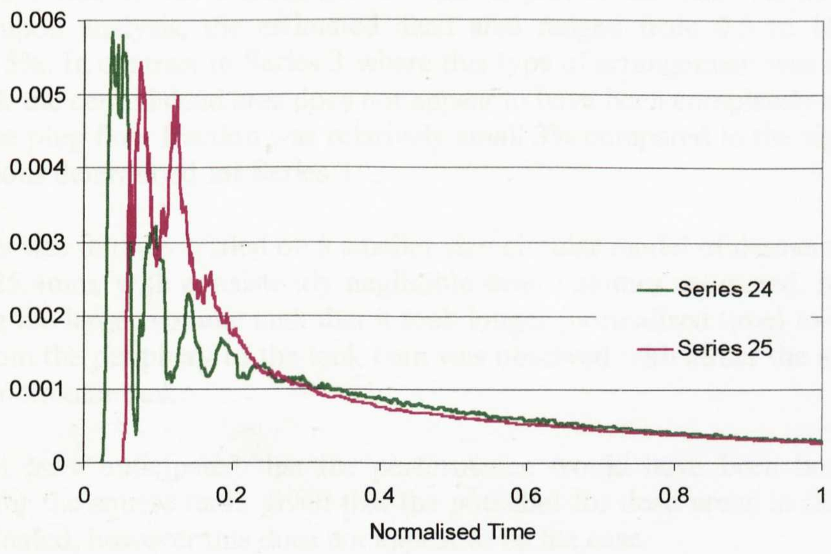


Figure 5.63 - Series 24 & 25: RTD curves.

5.6.5 Series 25: Inlet parallel to tank circumference: central outlet.

A modification to Series 24 was trialed using a central outlet to assess whether the dead area could be reduced, similar to that trialed in Series 5. Again a strong peripheral recirculation pattern is formed. During steady state tests the flow spiralled into the central outlet. One complete circulation occurred before flow began to spiral into the outlet, Figure 5.64. Three peaks were evident before exponential decay. In comparison with Series 24, the reduced normalised time between the first and second circulations indicates that the flow had begun to spiral into the centre of the tank by the second circulation. The percentage of the inlet flow passing out on the first circulation was reduced to 2.8 %. Mixing was good, CV 0.15, however the time taken to achieve mixing was long 0.55T. Continuous inlet and outlet flow was required to maintain performance.

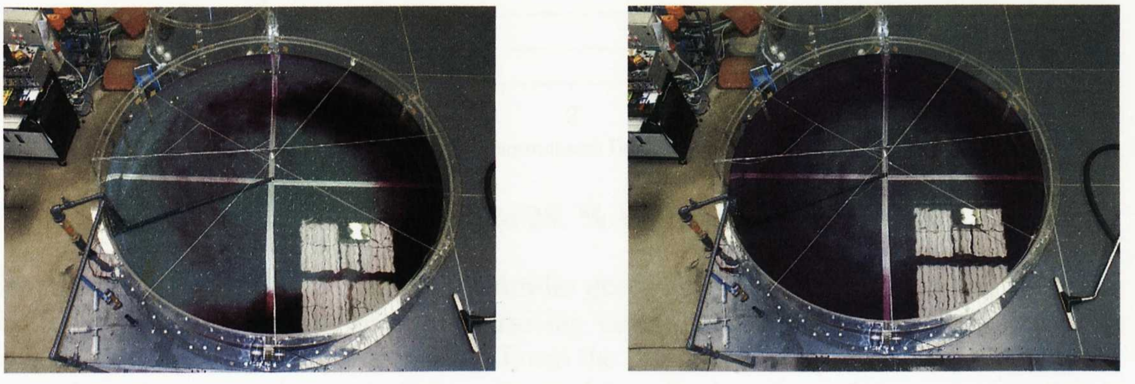


Figure 5.64 - Series 25: Dye test: Inlet flow 0.9 l/s

From the dye tests it was evident that the central part of the tank was no longer dead. However upon analysis, the estimated dead area ranged from 0.3 to 15%, typically closer to 15%. In contrast to Series 3 where this type of arrangement was evaluate for a square tank the central dead area does not appear to have been completely eliminated. In addition the plug flow fraction was relatively small 3% compared to the significant plug flow fractions determined for Series 3.

This Series was initially trialed on a smaller size circular model of diameter 1.3 m, inlet diameter 25.4mm, with consistently negligible dead volumes estimated. It was notable that during the larger volume tank that it took longer (normalised time) to visually clear the dye from the periphery of the tank than was observed with either the square tank or the smaller circular tank.

One might have anticipated that the performance would have been better than that observed for the square tank, given that the potential for dead areas in the corners has been eliminated, however this does not appear to be the case.

The results cannot be considered anomalous; as for all previous Series, estimation of dead volumes from analysis of the RTD curves have corresponded with visual assessment of dead volumes from dye tests.

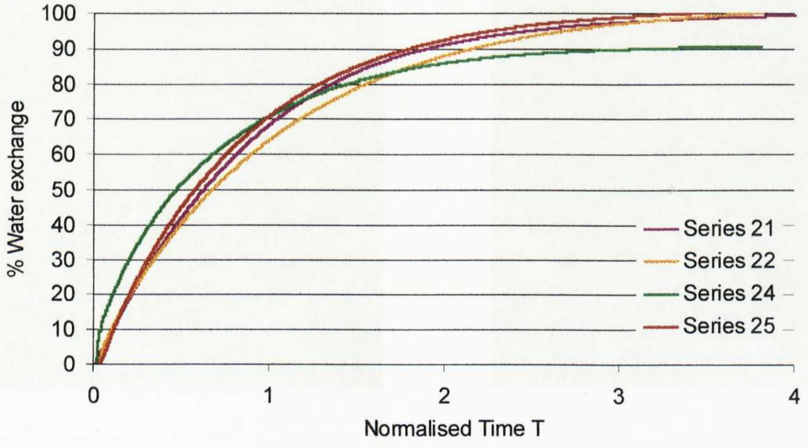


Figure 5.65 - Series 21 to 25: % Water exchange curves

Several investigators have evaluated a similar geometry, see Tables 3.2 & 3.4. However the focus of the work has been on optimising minimum retention time for disinfection rather than achieving complete mixing. From the limited results presented the values for t_{10} and t_o are reported are similar to those determined under steady state conditions during this study (Appendix D) taking into account the difference in measurement techniques.

5.6.6 Series 26: Upturned bellmouth above TWL: Outlet directly opposite.

During steady state flow conditions the annular inlet jet plunges to the base of the tank and begins to spread out radially from the point of injection. However, the majority of the flow short-circuits around the circumferential wall with slower moving flow through the centre. As the circumferential jets meet at the outlet, the flow returns through the centre of the tank, resulting in twin circulation cells that were not symmetrical with the potential for small dead areas in the centre of each circulation or a dead area in the centre of the tank. Estimated dead volumes were consistently high, 26% with the remainder of the tank being mixed flow, table 5.18.

A typical RTD curve is shown in Figure 5.67, which exhibits the twin initial peaks from the circumferential jets and weak re-circulation in the exponential decay. Although dead areas occurred, the time to achieve water exchange was good, Figure 5.69.

The measured CV was 0.14 and the time to achieve mixing under steady state conditions was 0.37T.

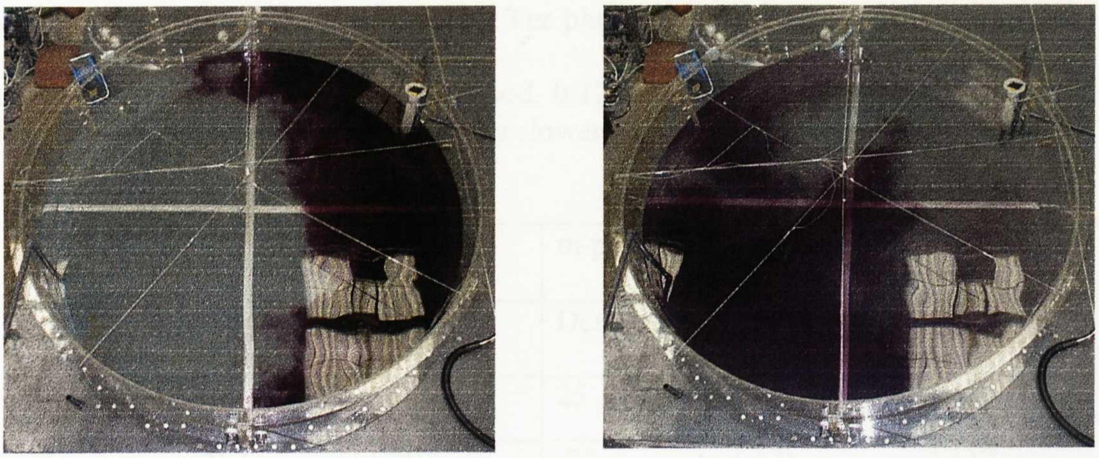


Figure 5.66 - Series 26: Dye tests

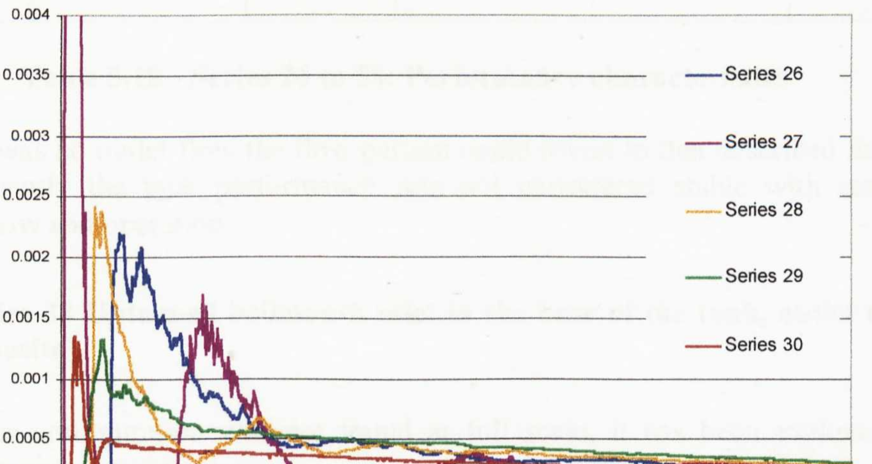


Figure 5.67 - Series 26 to 30: RTD curves

5.6.7 Series 27: Upturned bellmouth above TWL: base level adjacent outlet.

A number of sites surveyed had upturned bellmouth inlets, which were not at a maximum distance from the outlet. In some instances the outlet was at base level adjacent the inlet.

During the steady state and transient state tests conducted on this Series it was evident that the flow pattern in the tank could be severely biased by the position of the outlet leading to a single circulation cell being established in the tank in one direction around the tank. This resulted in more pronounced recirculation in the tank (Figure 5.67). In contrast to Series 26, the dead volume reduced to a negligible level (see Table 5.18) while short-circuiting increased to 20%. The plug flow fraction was small as 5.6 %.

Although the final CV reached was good, 0.12, the time to achieve mixing was very slow 1T. Water exchange was noticeably slower than for Series 26.

		T_{mean}	m-p model		
Series	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
26	6.7	26.8	25	1	76
27	20.2	0	-23	5.9	117
28	15.7	9.9	5.9	2	91
29	3.8	0	-7	7	99
30	4.8	16.2	17	7	74

Table 5.18 - Series 26 to 30: Performance characteristics

When there was no outlet flow the flow pattern could revert to that described for Series 26. Consequently the tank performance was not considered stable with respect to changes in flow and operation.

5.6.8 Series 28 Upturned bellmouth inlet in the base of the tank, outlet directly opposite

Although this configuration was not found at full scale, it has been evaluated by a number of previous investigators.

During this study under steady state conditions the flow pattern established in the tank was typically twin circulations. Flow rose from the low level inlet and began to spread out across the surface of the tank. The flow then split to form two discrete jets that progressed around the circumference of the tank, one clockwise and the other anticlockwise. The jets then turned to form circulation cells. Similarly with Series 26 the symmetry of the recirculation cells was a function of the flow split at the surface of the tank, which is likely to be a function of the exact placement of the inlet pipe. The dead volume in the tank was estimated to be between 6 and 10 %, the remaining fraction of the tank being predominantly mixed flow.

The resulting RTD, figure 5.67 shows that there is typically a large initial peak with some weak recirculation in the tank. The measured mixing achieved was good CV 0.09 and time to achieve mixing good 0.152 T.

It should be noted that this configuration would lead to the inlet flow being directed up to the surface of the tank. It is likely that the inlet flow would have a higher chlorine residual than the level in the tank and therefore there is a risk that the arrangement will result in an increase chlorine residual loss to atmosphere across the reservoir.

5.6.9 Series 29: 45°downturned bellmouth above TWL: outlet directly opposite

This arrangement was trailed as a potential improvement on Series 26. During the steady state tests the inlet jet plunged to the base of the tank and began to spread out radially from the point of injection.

The increased forward momentum ensured that the inlet jet progresses through the middle of the tank, before splitting to form two (clockwise & anticlockwise) recirculation cells that progressed back towards the inlet around the circumferential walls.

No significant dead areas were determined and the remaining tank volume behaved like mixed flow with an estimated 7 % plug flow.

Good mixing was achieved (CV of 0.17) in a very short time 0.1T, the negligible dead areas and good mixing contributing to rapid water exchange.

The RTD curves show that there is a single dominant peak followed by exponential decay with no evident re-circulation in the tank.

During the dye tests it was difficult to ascertain the flow path taken as some of the inlet flow became rapidly entrained in the re-circulating flow. This accelerated the dispersion of the incoming trace.

The performance was stable with respect to transient flow tests and did not deteriorate during the intermittent flow tests.

5.6.10 Series 30: 45° downturned bellmouth above TWL, outlet at base level.

This series of tests were derived from Series 29 as a potential simple retrofit option for Series 27.

During the steady state tests the inlet flow began to spread out radially from the inlet and then became rapidly entrained in the recirculation flow pattern back towards the outlet. 4.8 percent of the inlet trace circulates and leaves in the initial RTD peak. The RTD curve shows that there is a single dominant peak followed by exponential decay with no evident re-circulation in the tank, Figure 5.67.

The estimated dead volume in the tank increased to 16% as a function of relative outlet position. The final CV achieved was good, 0.12, which did not reflect the increase in dead areas in the tank and the time to achieve mixing was good 0.15T again possibly due to the speed of entrainment of incoming flow in re-circulating flow patterns.

The water exchange curve is shown in Figure 5.69.

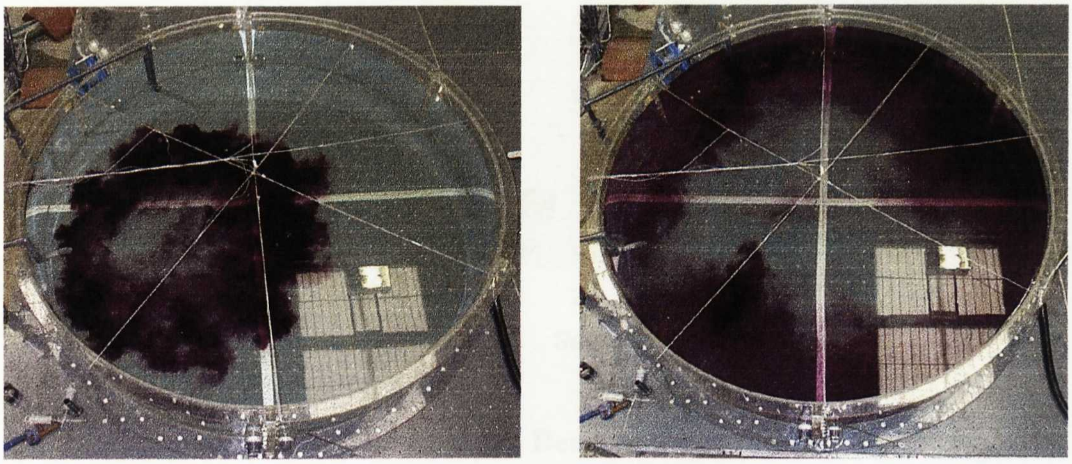


Figure 5.68 - Series 30: Dye tests: Inlet & Outlet flow 0.9l/s.

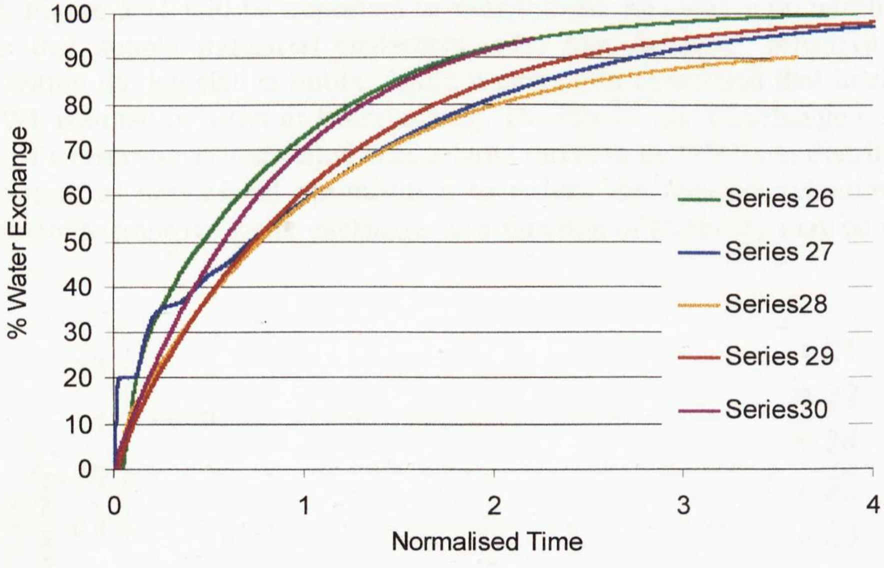


Figure 5.69 - Series 26 to 30: Water exchange curves

A simple plot of percentage dead volume versus short-circuiting as shown in Figure 5.70 gives a strong indication of which inlet and outlet arrangements perform well under steady state conditions. Short-circuiting may be an issue if a reservoir is associated with a treatment works that is prone to periodic minor infringements of water quality parameters. However one would need to take into account which arrangement was robust with respect to operational changes.

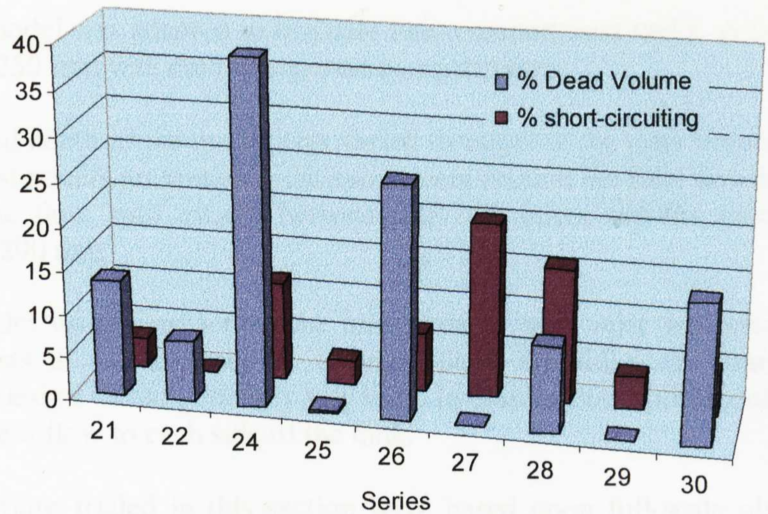


Figure 5.70 - Series 21 to 30: Dead volume and short-circuiting*

* It should be noted that the results for Series 25 represent the minimum estimated dead area for this arrangement and some of the steady state tests indicated dead areas up to 20% of the tank volume.

While elimination of dead volumes is a primary concern the rate of mixing and mixing achieved, Figure 5.71 will be important to sites that are operated with intermittent flow and sites that supply industrial customers, who may be more sensitive to quality changes within the legislative limits. Again it cannot be concluded that inlets above or below TWL resulted in better or faster mixing. The rate of water exchange may be a key criterion. If a reservoir is associated with a large increase in THM's in distribution, then a combination of operational optimisation to reduce the nominal retention time and refurbishment to improve water exchange, as a function of geometry may be required.

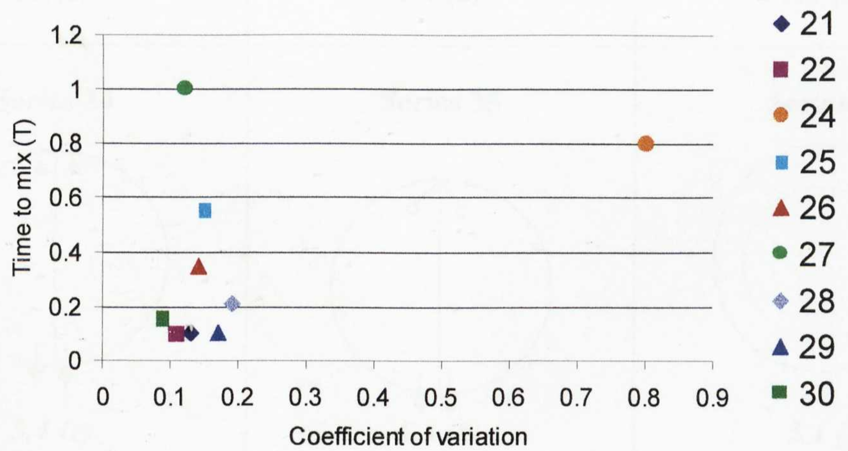


Figure 5.71 - Series 21 to 30: CV & Normalised mixing time (T)

5.7 Circular tanks with dividing walls

The circular model was adapted to evaluate twin compartment tanks. A central dividing wall of depth 250 mm was used to separate compartments.

The operational depth of the model was varied throughout the tests from and m. For the steady state test results presented in the subsequent section the inlet flowrate was set at t 0.9 l/s and the flow split evenly between the two inlets and the model depth was maintained at 290 mm.

When the model was being set up the inlet flow to each inlet was measured, during subsequent tests it was assumed to be equivalent. On full-scale twin compartment reservoirs the design would generally rely upon hydraulic flow splitting of this nature to assure equivalent flow to each side of the tank.

The configurations trialed in this section were based upon full-scale plant designs or potential modifications to existing designs and are shown in Figure 5.72. The subscripts in italics cross-reference the arrangement position in the design guide document Appendix D.

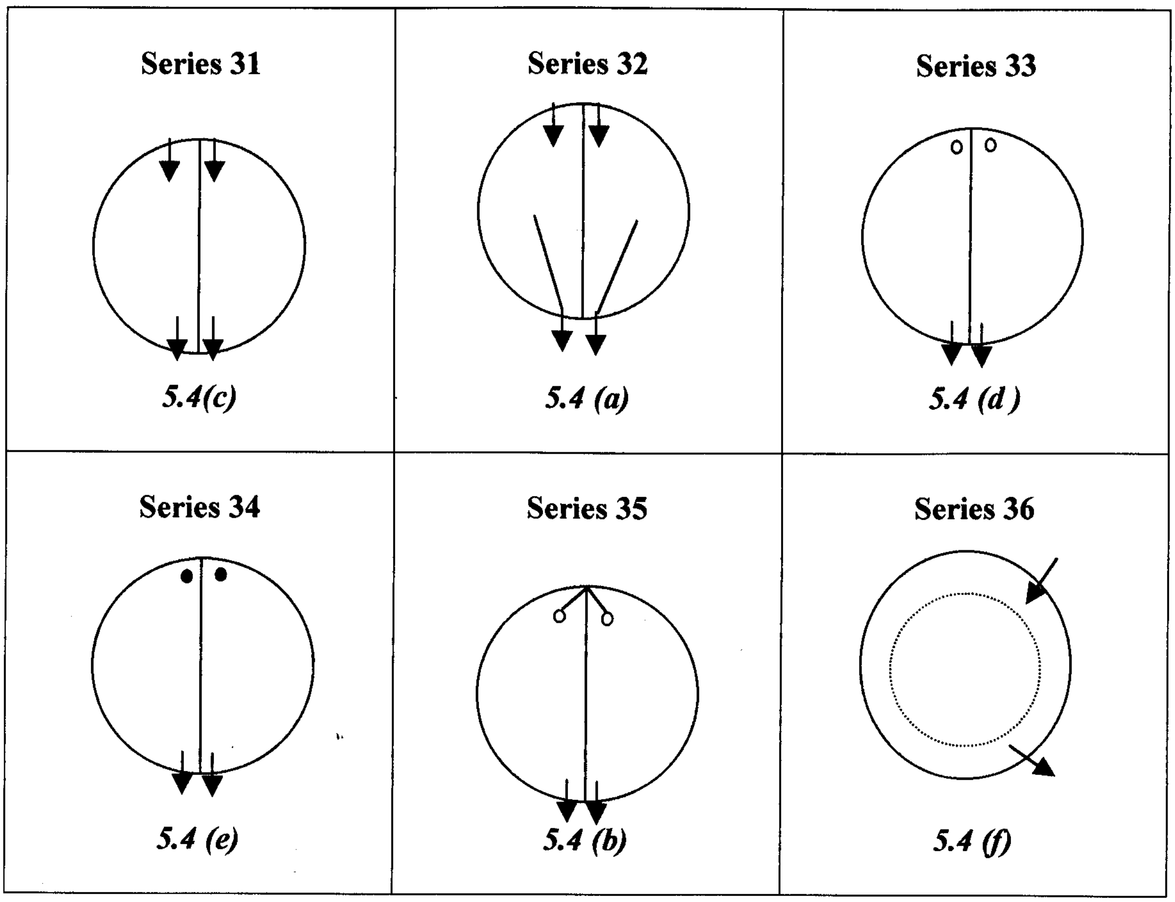


Figure 5.72 - Schematic of circular twin compartment tanks

5.7.1 Series 31: Horizontal straight pipe inlets, outlets directly opposite, parallel to dividing wall.

During all of the steady state tests the central dividing wall was submerged. As one might anticipate from previous results, the inlet jet short circuits along the central dividing wall to the outlet then follows the circumferential wall back towards the inlet. Resulting in a peripheral circulation in each half of the tank, with a small central dead area, see Figure 5.73. Crossover at high level appeared to be minimal and did not have an evident influence on the overall flow pattern in the tank.

The resulting RTD curves showed multiple circulations, typically three in the tank and each compartment. The RTD curves shown in Figure 5.74 are for the combined outlet flow from both halves of the tank.

The estimated dead volumes in the tank were typically between 7.2 and 20 % (t_{mean} and m-p method respectively), with 13% of the inlet flow short-circuiting to the outlet. The remainder of the tank behaved as mixed flow. Reasonable mixing was achieved, CV 0.18, in 0.266 T. The time to achieve water exchange was also good in comparison with similar arrangements (Series 1, Series 21) for other geometries, see Figure 5.75.

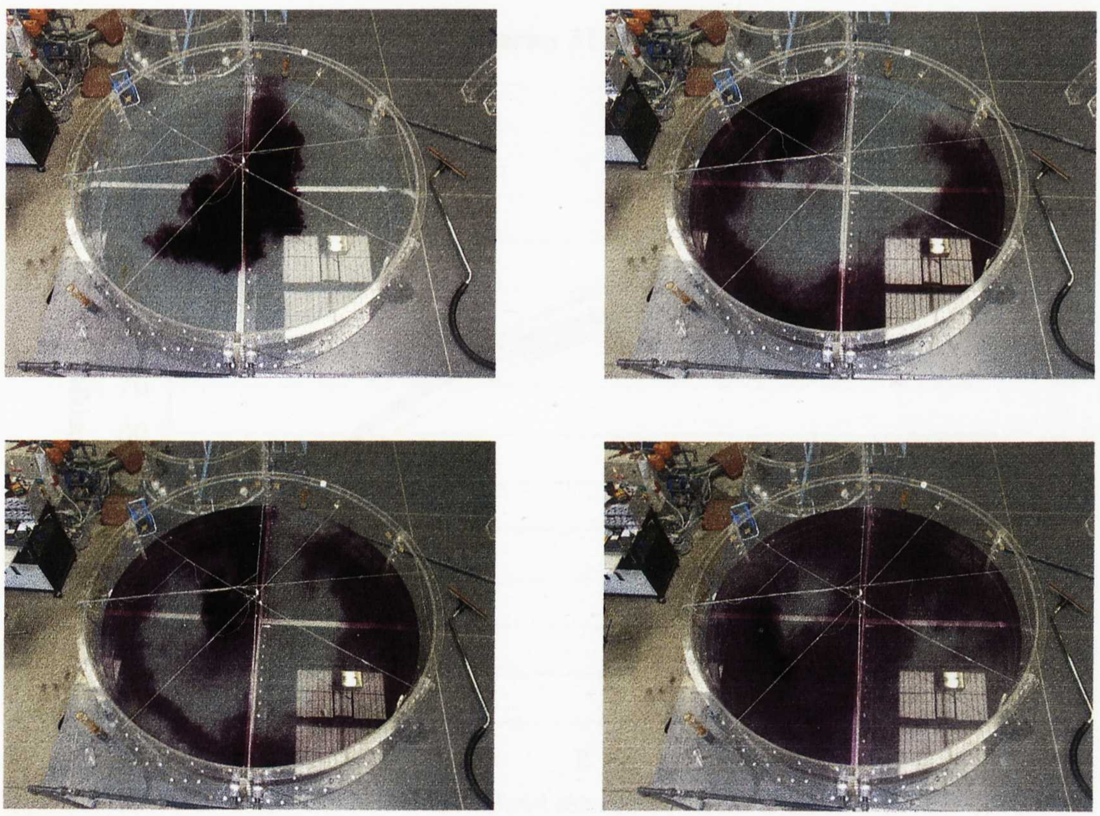


Figure 5.73 - Series 31: Dye test: Inlet flow 0.45 l/s per compartment, tank depth 0.29m

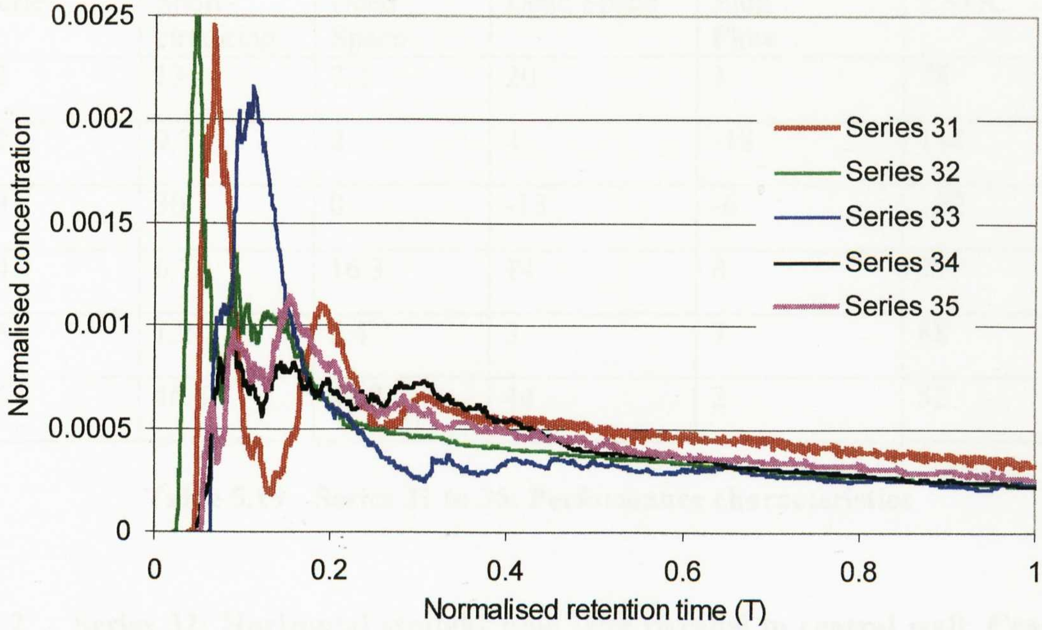


Figure 5.74 - Series 31 to 35: RTD curves

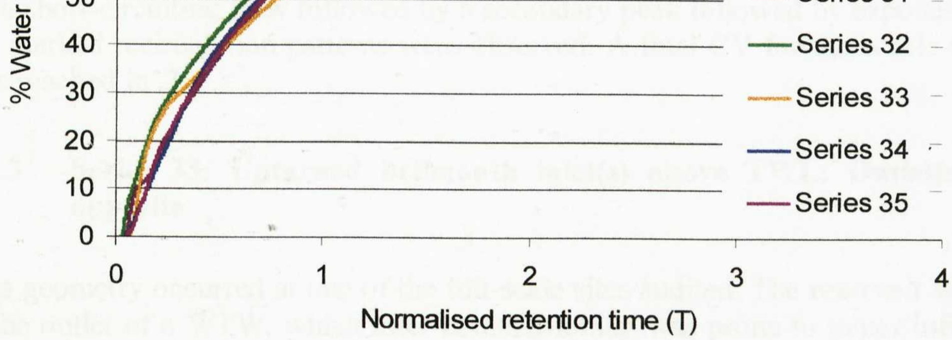


Figure 5.75 - Series 31 to 35: Water exchange curves

		T_{mean}	m-p model		
Series	Short-circuiting	Dead Space	Dead Space	Plug Flow	CSTR
31	13.1	7.2	20	1	78
32	9.7	2	4	-18	114
33	30	0	-15	-6	122
34	6.7	16.3	14	8	77
35	1.2	5.4	3	7	88
36	46.5	48.2	44	2	52

Table 5.19 - Series 31 to 36: Performance characteristics

5.7.2 Series 32: Horizontal straight pipe inlet parallel to central wall: Central outlet

This series was considered as a potential retrofit option for Series 31. During the steady state tests the inlet jet in each compartment progressed along the central dividing wall. The leading edge of the flow turned before it reached the opposite side of the tank and began to spiral into the centrally positioned outlet, approximately 9.7 % of the inlet trace leaving in the first circulation. Strong circulation flow patterns resulted in each compartment. The highest velocities occurring in the zone in each compartment situated between the inlet and the outlet. The velocities in the remaining volume were reduced, though no significant dead areas occurred. The m-p and T_{mean} models predicted dead areas between 2 and 4 %. In contrast to Series 3, no plug flow fraction was predicted and the remainder of the tank was mixed flow.

Typical steady state RTD curves, figure 5.74 showed a single large peak synonymous with short-circuiting flow followed by a secondary peak followed by exponential decay. No marked recirculation patterns were observed. A final CV for the whole tank of 0.2 was reached in .3 T.

5.7.3 Series 33: Upturned bellmouth inlet(s) above TWL: Outlet(s) directly opposite

This geometry occurred at one of the full-scale sites audited. The reservoir was situated at the outlet of a WTW, which after commissioning was prone to minor infringements of the PCV for iron (200 µg/l). The iron level leaving the works was typically less than 50 µg/l. A failure at the treatment works was resulting in subsequent failures in all of the supplied zones even though the nominal residence time in the reservoir was greater than 24 hours and the duration of high final water irons at the works were typically short - less than 1 hour.

In each compartment, during the steady state tests the inlet jet plunged to the base of the tank and began to expand radially. The plume then split into two discrete jets, the dominant jet followed the circumferential wall reaching the outlet first, resulting in 30% of the inlet flow short-circuiting to the outlet. The second jet progressed part way down the central dividing wall before turning to form a circulation in towards the centre of the tank. The dye and RTD trace analysis indicated that there were no significant dead volumes. Considering the extent of the short circuiting flow the m-p model did not predict any plug flow fraction (Table 5.16). The final CV was 0.2, however the time to achieve mixing was poor at 0.5 T.

A typical RTD in Figure 5.74 shows the large initial peak at 0.1T followed by a marginal secondary peak and exponential decay. It was apparent that the short-circuiting under steady state conditions was pronounced. During transient and intermittent flow tests the flow pattern in the tank remained the same. Hence a large degree of short – circuiting was assured irrespective of operating conditions.

5.7.4 Series 34 Downturned bellmouth inlet(s) above TWL: Inlet and outlet directly opposite

During the previous trials of a downturned bellmouth inlet, the increased momentum resulted in improved initial radial spread of the inlet flow. This Series was considered as a possible minor modification of Series 34 to reduce short-circuiting.

During the steady state tests the inlet plunged to the base of the tank and began to spread radially. Again the flow divides into two dominant jets however in this instance the dominant jet short-circuited along the central dividing wall to reach the outlet first. The reduction in t_0 (0.047 T) when compared to Series 34 (t_0 = 0.064 T) was indicative of the shorter flow path length taken. The flow then turns forming a circulation into the centre of the compartment.

The secondary jet takes the circumferential path and also turns into the centre of the compartment, resulting in two circulation cells in each half of the tank.

The short-circuiting was reduced significantly to 6.7%, the calculated dead volumes increased to 16%. The m-p model predicted a significant plug flow fraction in the tank, 8%, Table 5.16

The mixing achieved was comparable to Series 33, CV 0.21 in normalised time 0.53 T.

Again during the transient and intermittent flow tests the flow pattern remained similar.

5.7.5 Series 35: Downturned bellmouth angled at 45° towards centre of compartment outlet directly opposite

This series of tests was conducted as a possible retrofit option to Series 33. The resulting flow pattern during steady state tests could be considered to be a variation of Series 33 and Series 34 tests. The inlet flow separating into two jets that progressed along the circumferential and central wall respectively. In this instance there was superior initial dispersion of flow towards the centre of the tank with the result that observed short-circuiting was reduced to 1.2%. The estimated dead areas were between 3 and 7%. The plug flow fraction was roughly 7% with the remaining dominant fraction of the tank mixed flow (table 5.16).

The RTD curve, Figure 5.74 shows that there are three circulations before exponential decay. The circulation time is much reduced compared to Series 31 confirming that a smaller volume of the tank is concerned with the particular re-circulation cell. The final CV achieved was good, 0.1 and the mixing time reduced to 0.45T

5.7.6 Series 36: Horizontal straight pipe inlet and outlet in external chamber: Central circular mid height dividing wall.

This Series of tests resulted from a full-scale plant design that was subsequently modified. At the time of the initial modelling programme the position of the actual operational inlet and outlet were not clearly defined.

During the steady state tests flow from the inlet progressed around the outer compartment to the outlet. Some of the flow passed under and over the central circular division wall into the central compartment. However, as might be anticipated from this arrangement short-circuiting was excessive greater than 40% of the inlet flow and an estimated 48% of the tank volume was dead. Mixing was very poor (CV of 0.35) and the time to achieve mixing long. The central compartment was in fact 50% of the tank volume. The m-p model did not however predict a significant plug flow fraction (2%), Table 5.16

Whilst one might have anticipated a poor performance as a result of such an arrangement. Previous designs have been based on a simplistic and often erroneous belief that if a central dividing wall is submerged then adequate water exchange between compartments can be achieved.

5.7.7 Circular twin compartment results comparison

A simple plot of percentage dead volume versus short-circuiting as shown in Figure 5.76 gives a strong indication of which inlet and outlet arrangements perform well under steady state conditions.

Selection of an appropriate design from these arrangements will result in a compromise between accepting a degree of short-circuiting and minimising dead volumes.

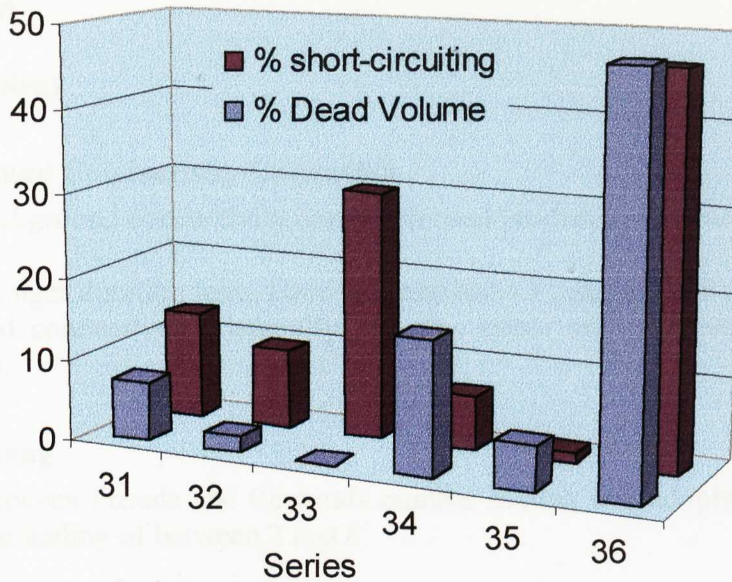


Figure 5.76 - Series 31 to 36: Percentage dead volume and short-circuiting

The calculated values for CV and time to achieve mixing were variable for relatively minor changes in inlet orientation, as shown in Figure 5.77. Consequently the Okita and Oyama (1963) model correlation was poor.

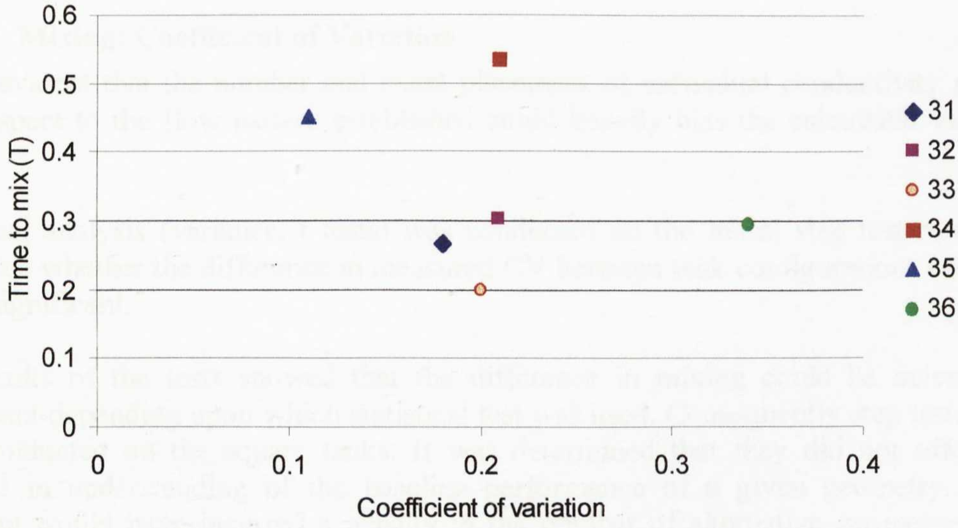


Figure 5.77 - Series 31 to 36: CV & Normalised Time to achieve mixing

Case Studies

The implications of reservoir performance on water quality are presented in the form of four case studies included in Appendix D.

6 Discussion

6.1 Methodology

6.1.1 Background Conductivity Correction

The method of background conductivity correction used produced reproducible results.

For some of the longer duration tests, there still remained a tendency for a gradual drift in the background conductivity. Generally this was minor and occurred in the final stages of the RTD.

6.1.2 Flow scaling

A compromise between Froude and Reynolds number scaling was adopted, typically a multiple of Froude scaling of between 2 and 8.

The method produced reproducible results that were verified by full-scale lithium tracer tests. Distorted vertical scale modelling techniques were also used.

Effects of modelling at shallow depths were observed and noted. This raised concerns over some of the scaling criteria, shallow depths of models and low inlet velocities reported in the literature. Under these conditions the boundary effects are unlikely to be negligible, however they are not reported in the literature.

6.1.3 Mixing: Coefficient of Variation

It was evident that the number and exact placement of individual conductivity probes with respect to the flow pattern established could heavily bias the calculated value of CV.

Statistical analysis (variance, t tests) was conducted on the initial step test results to determine whether the difference in measured CV between tank configurations could be called significant.

The results of the tests showed that the difference in mixing could be determined significant depending upon which statistical test was used. Consequently step tests were only conducted on the square tanks. It was determined that they did not offer any increase in understanding of the baseline performance of a given geometry. Their inclusion would have incurred a penalty in the number of alternative geometries that could be evaluated.

Coefficient of variation measurement does remain the most appropriate method for qualitative measurement of mixing performance in a tank, pipe or channel. Placement and number of monitoring points is critical to the reliability and significance of the results.

Alternative approaches to the inclusion of vast numbers of conductivity probes within the model must be sought. Analysis of the digital flow visualisation video recordings made during the study could be could be undertaken to provide an unbiased calculation of CV and potentially determine the velocity profile within the tank.

6.1.4 Mixing Models

A number of empirical mixing models were evaluated to assess their potential for predicting mixing time as a function of changing tank configuration. In this study, their application proved successful in determining a mixing time relationship for a single geometry operated over a range of steady sate conditions.

The model coefficients (K) were markedly different from those reported in the literature. This was anticipated as a function of the different experimental methods and mixing determinants used.

When the models were applied to a cross section of the steady state square tanks results (Series 1, 2, 3, 11, 12, 13) there was no apparent correlation for any of the models evaluated. Table 6.1.

Author	**Series 1** **Fixed inlet and outlet position** Steady state test	**Aspect ratio 1:1** **Steady state tests**
Okita & Oyama	K=15 $R^2 = 0.953$	K=4.6 $R^2 = 0.002$
Fox & Gex	K=5653 $R^2 = 0.881$	K=1083 $R^2 = 0.006$
Fosset & Prosser	K=60551 $R^2 = 0.5877$	K=1x e^{-5} $R^2 = 0.01$

Table 6.1 - Mixing model coefficients and correlations

Consequently, the use of any of these models in the form outlined in the literature to predict mixing times in tanks with different internal geometry and inlet – outlet flow is not recommended.

The recently issued American Water Works Association report, 90774, Water Quality Monitoring In Distribution System Storage Facilities, for example, gives guidelines on mixing for square, rectangular and circular tanks. The authors report good mixing but different times for mixing for all inlet types and positions evaluated. The test results were generated in fill mode only and the outlet position for the series of tests is not given. Therefore these results cannot be applied to tanks that have separate inlet and outlet pipework or operate with some level of continuous inlet and outlet flow.

Where a mixing time relationship needs to be established for a specific geometry it is recommended that a Series of steady state tests are conducted to assess the mixing time and an appropriate coefficient K derived using the Okita and Oyama (1993) model. It is feasible that the model could be adapted to introduce coefficients for relative inlet and outlet position, type and relative momentum.

6.2 Modelling programme results

6.2.1 Flow pattern stability

The results show that the nature and relative position of both the inlet and outlet were critical in determining the flow pattern in the tank. The flow pattern determined the macromixing that occurred and consequently the relative position and volume of dead areas.

Dead areas are commonly referred to. They relate to volumes of fluid that are very slow moving. The rate of exchange of fluid between these areas and the bulk flow is very low.

6.2.2 Stable flow patterns

For specific inlet and outlet arrangements the flow pattern and inherent performance did not change significantly as a function of changes in steady state conditions (fixed operational depth, inlet–outlet flowrate). The performance as measured in terms of dead, mixed and plug volumes, short-circuiting and CV also proved robust during transient tests, where the ratios of inlet – outlet flowrate, momentum and model level changed. The performance of designs of this type may be considered to have a degree of stability with respect to normal operational changes.

6.2.3 Unstable flow patterns

For other inlet and outlet arrangements typically, but not exclusively those with inlets and outlets in relatively close proximity, the steady state flow pattern and inherent performance changed as a function of alterations in steady state conditions. In some instances, marked changes in the flow pattern and inherent performance were noted. Performance ranged at one extreme from a completely mixed tank, to a tank with dead volumes in excess of 20%.

The performances of designs of this nature are consequently considered "unstable" with respect to normal operational changes. Volumes of fluid in the reservoir that have remained relatively quiescent under specific operational conditions become entrained in high velocity recirculating flow as the operational conditions change.

If this occurs on a daily basis, then older water is unlikely to accumulate one might anticipate fluctuating chlorine residuals.

If changes in flow pattern of this nature occur rarely, it is feasible that they will be associated with volumes of older water with indefinite quality characteristics being flushed into the distribution system. This could result in compliance failures and customer complaints.

Of the reservoir configurations trialed, few would be considered as having stable flow patterns for all extremes of operation. It is important to define and understand the operational boundaries beyond which the performance will deteriorate.

6.2.4 Multiple inlet–outlet configurations

The potential for the development of "unstable" flow patterns is compounded when one considers multiple inlet and outlet designs. Unless the inlet flows are combined and act as essentially one inlet source, or their relative position(s) are such that they reinforce the dominant flow pattern under all operational conditions, then the risk of complex and constantly changing flow patterns is high.

Again, if these transient states occur frequently, direct implications on water quality may in fact be minimal. The changes could in fact promote better mixing.

Quality implications should be anticipated where a reservoir is operated within fixed tolerances for prolonged periods of time (several days) and then the mode of operation is changed. An example of this is given in case study 4 in Appendix C.

6.2.5 Common inlet - outlet tanks

The tests conducted on common inlet and outlet or push pull tanks indicated that these tanks are less prone to unstable flow patterns as they can only operate in true fill and draw mode. Conversely, the nature of the design means that frequency, volume and duration of inlet flow cannot be assured and consequently poor mixing and extremes in water age can result.

When conducting the tests under lamina flow conditions these tanks did not appear to operate on a last in first out basis. The inlet flow had sufficient momentum to move away from the inlet. In general it followed a similar flow path to that which might have been taken if the inlet jet were turbulent. No entrainment of surrounding flow occurred and mixing was correspondingly poor. This concurred with the results presented for non-turbulent jets presented by Reynolds (1962) and McNaughton (1966).

It should be noted that the modelling did not take into account the implications of thermal stratification.

6.2.6 Intermittent flow tests

Due to programme constraints a single test was conducted in the same manner for each Series evaluated. Inlet and outlet flow was introduced successively for periods of ½ the nominal model retention time and then terminated. This sequence was repeated for a period of at least four nominal retention times in each case.

In all cases the injected tracer was reasonably mixed by the end of the initial inlet flow period. The subsequent periods of outlet, then inlet flow etc, simply washed out, or diluted the trace concentration accordingly.

The internal tank probes indicated that flow was moving past the probes continuously when the inlet flow was off. A probe in stationary flow showed an exponential rise in conductivity.

It was concluded that the intermittent flow tests conducted provided limited information on the minimum duration of inlet flow required to mix the tank. It would have been more appropriate to conduct a Series of tests where the flow pattern in the tank was established and the inlet flow then terminated directly after the tracer pulse was injected.

6.2.7 Implications

It can be tempting to conduct an experimental study and present unequivocal results on the performance of a given reservoir design. The modelling programme has shown that the actual results generated, the methods by which they were obtained and the limits of applicability must be clearly defined to prevent the application at full scale of a design that is not hydraulically robust for the full range of operational conditions it will encounter.

6.3 Multiple circulations in rectangular tanks

Numerous authors have compared CFD simulations with physical modelling studies and full-scale plant data, generally with reasonable correlations.

When modelling the rectangular tank it was evident that at aspect ratios of 2:1 multiple circulations were being established in the model. When the aspect ratio had increased to 2.4:1, twin circulations were firmly established. This turning effect on the flow was not predicted or indicated by CFD simulations conducted for a similar aspect ratio of tank with the same general inlet and outlet arrangement (Morrison, 1999). It is feasible that CFD simulations would predict this at a different aspect ratio. Further CFD simulations would need to be carried out with the same boundary conditions as the physical model.

It is not clear whether these twin and triple circulation cells were a function of the aspect ratio of the tank and boundary layer effects in the model. Full-scale plant lithium data was not available for tanks with aspect ratios of greater than 2:1. This should be carried out.

At this juncture the phenomenon is considered to be a real flow effect.

In addition to confirmation full scale lithium tracer tests, confirmation of predicted modelling flow patterns can be corroborated by comparison of predicted dead zones in the model with prototype sludge deposition zones.

6.4 The Coanda effect

Flow adhering to the walls of the model was commonplace in a number of geometries due to the Coanda effect. The scaling of positioning of inlet pipework was accurate on the model. For Series 1 & 2 type geometries relocating the inlets away from the side walls should reduce the central dead volume. This should be relatively easy to calculate from equation 2.17. Physical modelling tests would be recommended to evaluate the potential change in performance. It is considered unlikely that these minor modifications would eradicate the central dead volumes in square or circular tanks of this type. It is feasible that they may be substantially reduced.

As the aspect ratio is increased 1:1 to 2:1 in rectangular tanks it may be of substantial benefit. If this is found to be the case then the design document Appendix D, should be modified to include guidelines for placement of inlet and outlet pipework relative to the tank walls.

The Coanda effect contributed to the multiple circulation patterns established in tanks with inlets above TWL (Series 11, 12 etc). There may be limited scope for improvement of this design by marginal relocation of the inlet – outlet pipework. Generally the side walls are used to provide structural support for high level inlets consequently there would be engineering constraints in repositioning a high level inlet at substantial distances from a supporting wall.

6.5 Assessment of model flow fractions

The t_{mean} method and m-p methods used to estimate dead volumes showed good correlation for the steady state flows.

The t_{mean} method was very simplistic and less prone to the systematic errors that may be incurred during calculation of the flow fractions by the m-p model. However the t_{mean} method provides no insight into the plug flow fraction in the tank. The m-p model predicted significant plug flow fractions for a number of the Series trialed.

Series 3, 25 and 32 were similar inlet and outlet arrangements evaluated in different geometry tanks. All induced a peripheral flow circulation in the tank that then spiralled into a centrally positioned outlet.

The m-p model consistently predicted a significant plug flow fraction for the Series 3 tests. Conversely minimal plug flow fractions were determined for Series 25 and Series 32. This may be explained for Series 32 by the fact that the RTD was combined for both compartments. However it was anticipated the strong correlations between the flow factors would have been evident for Series 3 and 25.

		T_{mean}	**m-p model**		
Series	**Short-circuiting**	**Dead Space**	**Dead Space**	**Plug Flow**	**CSTR**
3	0	0	-16% to -5%	13 to 20 %	91 to 99 %
25	0	0.3 to 15	15	3	80
32	9.7	2	4	-18	114
16	20	0	-14	20	94
18	26	5	-30	2	128
33	30	0	-15	-6	122

Table 6.2 - Comparison of plug, mixed and CSTR fractions

Again comparison of the Series results shows that in individual cases there was an apparent correlation between short –circuiting and plug flow. However in cases where the short-circuiting is pronounced, Series 33 for example, the m-p model predicts a completely mixed reactor. Further work is therefore required to determine how the model predictions of flow fractions can be related to the flow visualisation tests.

It should be noted that previous authors have applied the mixed tanks in Series model and predicted that many reservoirs behave as completely mixed tanks. The mixed tanks in series model was used on all of the steady state experimental results generated. It did not provide any additional insight into comparative performance.

For example, when considering the combined results for Series 1 tests, where considerable dead volumes occurred. The mixed tanks in Series model predicted an average value for N of 1.29 mixed tanks with a standard deviation of 0.21. During the Series 3 tests the model predicted an average value for N of 1.21 mixed tanks with a standard deviation of 0.21.

Although the geometries trialed behaved predominantly as CSTR's, it is the dead volumes, plug flow and short-circuiting fractions that will have negative impact upon water quality.

The Dispersion model was also applied to all of the steady state test results. In the same manner the model did not provide any additional insight into performance. However this was not anticipated in this case as the conditions under which the model was derived do not apply to conditions were there are dead areas or severe by passing.

6.6 Twin Compartment Tanks

During this study twin compartment rectangular tanks were not modelled as whole tanks, each half of the tank was treated as a single entity.

Of the tanks surveyed, 13% of the twin compartment tanks were reported to have mid height separation walls. Of these tanks 99.3% had high-level inlets above TWL or horizontal straight pipe inlets at base level.

This is important as these inlet types, assuming neutral buoyancy inlet jets, will result in the highest initial velocities occurring across the base of the tank where the dominant flow pattern will be established. Hence any cross over that may occur between compartments at top water will be secondary.

Crossover and intermixing of the flow between the compartments did occur during circular, twin compartment modelling studies. In these instances it did not appear to significantly alter the flow pattern in either compartment.

The flow visualisations tests conducted unfortunately used the same colour of dye in each compartment, hence the true degree of cross over was difficult to visually assess. Further tests could be conducted where a salt trace is injected into a single compartment and recovered from the outlets of each, to quantifiably assess the volumes of cross over flow.

Only one of the full-scale tanks surveyed (0.7%) had a submerged vertical inlet pointing upwards and this was a single compartment tank. Inlets of this kind will result, again assuming neutral jet buoyancy, in the highest initial velocities occurring across the surface of the tank. In these circumstances crossover between compartments would be expected to be substantial.

A summary of inlet and outlet types is given in the design guide document in Appendix D.

6.7 The ideal service reservoir.

It goes without saying that a reservoir design must deliver its primary function in terms of ensuring security of supply and maintaining pressure. Another priority is that it should maintain the integrity of the incoming water. It is important to de-lineate good practice in design from operation. Certain practices in design will allow more flexibility in operation before infringing on water quality. In view of the increase in alternative supplies in distribution the ideal service reservoir design should:

- **Ensure that no dead areas exist under normal operation**

It is probably not feasible to ensure that dead areas or stratification do not occur at the extremes of potential future operation.

- **Achieve good and rapid mixing**

Ideally 95% mixing should be achieved so a CV of 0.05 would be a target value, in practice this was rarely achieve by any design evaluated. Therefore a more achievable target may be a CV of 0.1. This highlights the fact that there are limits to the blending quality that is likely to be achievable with the current design of service reservoirs. Therefore they may not be appropriate for blending sources of water with contaminants above the PCV threshold.

In an ideal case mixing should be instantaneous. In practice this is not achievable if one relies upon the hydraulic macromixing induced from the inlet flow alone. However certain designs result in more rapid attainment of CV values of 0.1. In the results chapter timescales are presented in units of dimensionless time, a value of 0.1 T would be considered rapid mixing based upon the performance of the designs evaluated. However in full-scale application, if inlet flow is non-continuous it is important that mixing is achieved well within the duration of the inlet flow period.

Achieving good mixing, as opposed to plug flow should minimise the disinfectant losses across the reservoir.

- **Achieve rapid complete turnover of the tank contents when operating under steady state conditions**

It must be feasible to completely exchange the contents tank without the requirement to change the operational level – or work the reservoir. Ideally this should be achieved in the shortest timescale possible. Complete and rapid water exchange would limit the formation of disinfection by products and reduce the risk of taste and odour and de-nitrification. It is important that this can be achieved under steady state conditions, as the design should not impose operational criteria that may not be adhered to when in operation.

- **Ensure that short circuiting does not occur**

- **Be hydraulically robust with respect to changes in operation**

The designer cannot predict or enforce the boundaries of future operation of the reservoir. While caveats on best practice operational boundaries may be given at the time of construction. They may be lost or not given sufficient emphasis in the fullness of time. Therefore there remains an ethical question as to whether certain designs or retrofits should be recommended given the potential for deterioration in performance when not operated correctly.

No single design evaluated achieved the best performance with respect to all the above criteria. Hence no single design could be termed as the ideal service reservoir. Recommendations on reservoir design therefore need to take into account some site-specific data. For example the shape of the land area available may prohibit building a square tank. In addition compromises in terms of "ideal" performance may need to be made.

For example the series 3 arrangement evaluated resulted in good performance with respect to all of the criteria above bar the final one- " *hydraulically robust with respect to changes in operation*". This design might be preferred where multiple water sources are used and limitations of THM formation are required. However performance can be very poor when operated with intermittent inlet and outlet flow.

This design has been retrofitted at full scale at strategic sites where continuous inlet and outlet flow is currently assured. Even when written into the plant operating manuals there were still concerns that the specific reasons for the retrofit would loose emphasis over time.

With other unit processes performance will deteriorate if not operated correctly. To date apart from the WRc reports stating that reservoirs should be worked. No other operational criteria have been widely applied.

6.8 Generation of the design guide.

It became apparent during this study that the flow patterns generated within these types of tanks under various operational conditions were complex.

Nevertheless there was a need to interpret and present the results and recommendations in such a way that a non technical individual could:

- Assess the basic performance of a reservoir quickly
- Make valid decisions about the potential for improvement of the asset.
- Assess whether operational optimisation was required and what potential benefits would result
- Determine whether a reservoir design was acceptable

It was important to define the boundaries where the recommendations were considered to be applicable and highlight the risks if these boundaries were not adhered to in the future.

It was also important to ensure that the user was steered towards the appropriate course of action in each case.

For example in many instances operational optimisation may have a much greater impact upon water quality than a capital refurbishment or retrofit option. For one particular site, a business case had been presented to baffle a reservoir with associated quality non-compliance issues. The flows in and out of the reservoir were unquantified. The author recommended that a portable ultrasonic flowmeter be used on the inlet and outlet and level measurements recorded to gauge the nominal retention time. The results indicated that the nominal retention time of the reservoir was of the order of 100 days. The business case was redeveloped on the basis of redirecting flow through the reservoir to reduce water age or preferential abandonment.

As discussed in the previous section, no geometry trialed could be considered perfect in all respects. In addition a design engineer will need to operate within the constraints of the land area available for new reservoirs and the existing reservoir design for retrofits. Therefore the design guide followed the same shape and aspect ratio groupings as the modelling study.

The implications of storage on resulting water quality have been discussed in some depth in Chapter 1. Conducting the physical modelling programme and defining key aspects of measurement of performance produced a focus on what aspects of the reservoir performance were likely to impact most significantly on specific water quality concerns.

For example it is well established that increases in storage time lead to increased THM formation. Therefore it becomes self evident that to reduce the potential for THM formation one should reduce the storage time.

Table 6.3 gives a list of water quality issues with associated reservoir performance measures that provide a potential route to optimisation. Theses are not mutually exclusive. For example reducing dead areas will improve water exchange. This provided a simple tool to focus on particular aspects of a reservoir hydraulic performance that were important in the optimisation of specific water quality issues.

Eliminating dead areas is one performance measure, which had an impact on all of the quality determinants. Consequently this was taken as a key performance indicator in the organisation of the design guide document and provided the framework for relative ranking of the inlet and outlet arrangements in each generic grouping. Eliminating dead areas would be considered a prerequisite for any refurbishment project. A secondary factor was the percentage of flow short-circuiting.

Within each generic grouping, simple bar charts were drawn of series number versus percentage dead area, short-circuiting, time to achieve mixing and CV. A typical chart is shown in Figure 5.34. Comparisons of this nature made it easy to rank reservoir designs in order of performance criteria. The Series were ordered in terms of assuring zero dead volume; short-circuiting, achieving good water exchange and time to achieve mixing.

	Reduce nominal retention time	**Increase frequency & time of inflow**	**Reduce dead areas**	**Reduce short circuiting**	**Enhance water exchange**	**Promote good mixing**
Bacteriological compliance			*		*	*
THM formation	*		*		*	
Reduce chlorine loss	*	*	*		*	*
Erratic chlorine residuals		*	*	*		*
Variations in distribution water quality		*	*	*		*
Dirty water incidents		*	*			*
Sludge deposition			*			*
Taste and Odour	*		*		*	*
Nitrification	*		*		*	*

Table 6.3 - Routes to improved water quality

In cases where the performance is likely to vary with respect to changes in steady state flow or transient flow, the design is nominally given a lower performance rating. If significant detrimental changes in performance are anticipated as a result of operation with intermittent flow, then guidelines on operation are given.

In using the design guide it is important that the user understands what goals they wish to achieve.

If one considers the following examples:

Optimisation to reduce THM formation is likely to require

- Reduction in nominal retention time via operational means
- Retrofit to improve water exchange and eliminate dead areas

Optimisation to reduce non compliance in distribution as a function of incidence of failure at a challenged WTW

- Retrofit to reduce short-circuiting and optimise mixing.

Hence a single design will not always be a panacea for optimisation of all quality issues. More importantly retrofit recommendations and new designs should take into account the current and future mode of operation of the reservoir before a design is recommended.

6.9 Service reservoirs and cryptosporidiosis

Service reservoir performance is not evident in the discussions surrounding waterborne cryptosporidiosis outbreaks. Nevertheless they do not have a negligible effect in determining the extent of an epidemic. The design and operation of the reservoir can affect the number of people infected, the rate of onset of illness and the severity of illness.

Although *cryptosporidium* are endemic in the environment, large concentrations are released during lambing and calving seasons. Hence water borne outbreaks can be associated with periodic increases in oocysts numbers due to contamination of surface water supplies.

The number of oocysts ingested, the virulence of the species and the natural immunity of the individual determine the rate of onset and whether symptoms of the illness manifest themselves. The higher the concentration ingested the greater the probability of illness.

Service reservoirs with severe short-circuiting will result in poor dilution of a short-lived contamination event. In these instances the likelihood of illness due to a higher number of oocysts ingested may be increased.

In contrast, reservoirs with very good mixing may afford some protection by dilution of short duration contamination events. This may be a factor in correlating the number of recorded incidents where elevated oocyst concentrations have been recorded in WTW effluents with no reported cases of illness in distribution.

Obviously there is a fine balance between reducing concentrations by blending and exposing a greater number of people to lower concentrations, and exposing smaller populations to higher concentrations. Service reservoir modelling can be used as a means of estimating the concentration of oocysts in the treated water that individuals would have been exposed to during an outbreak. Information of this nature has hitherto not been available due to the relatively long incubation periods, 4 to 7 days between ingestion and onset of illness. See Appendix D case study 4.

6.10 Business Implications

Due to unforeseen extremes in demand the water distribution system will never attain a just in time approach to supply. However poor management of stock levels has financial and public health implications.

The main business output from this thesis is in the form of the design guide in Appendix D. While in a simple format it results in a significant change in focus in the operation and design of service reservoirs.

The design guide sets out some basic rules in terms of water age. It enables a user to convert a nominal storage time into a real time measure for actual water age. This approach brings a focus to decision making, clarifying the choices between possible optimisations strategies.

The user is guided towards operational optimisation first. The basic initial calculations required at the start of an assessment require the asset manager to determine the flows in and out of the reservoir and how it is operated as a starting point. Conducting the survey, it was clear that this information is not always available or easily accessible. So business decisions such as

- Clean
- Retrofit
- Reline the roof
- Abandon

Would be made with significant financial consequences in some cases without a clear demarcation of the benefit - risk of pursuing one option rather than another.

As a case study, if we consider SR's 3 and 4 as described in Chapter 1, with operational nominal retention times of 4.5 and 5.8 days respectively. With the most favourable design of reservoir it would take 3 times the nominal retention time to achieve water exchange. Therefore at best water exchange will occur in 13.5 days in SR3 and 17.4 days in SR4. THM non-compliance in the distribution system served by these reservoirs is being addressed by a six figure capital project to remove organics from the source water. Operational optimisation of the reservoirs to reduce the nominal retention time could lead to a short-term improvement in compliance. Reservoir refurbishment costs if required, would be anticipated to be less than 20K per site.

Where the appropriate design is used good water exchange can be achieved rapidly without the requirement to alter the top water level in the reservoir.

There are significant operational costs associated with ensuring that reservoir level are varied every 24 hours. Given that the practice does not eliminate dead areas, the risk of water quality non-compliance still remains. With the appropriate retrofit solution better mixing and elimination of dead areas can be assured.

For future design of reservoirs the design emphasis changed from volume storage, to design based upon future operation, this assures that future operation of the site is considered in depth before commitment to a civil design.

The decision trees in the document place emphasis on operational optimisation and set limits on acceptable water age. Highlighting the quality risk of maintaining excessive buffers for security of supply. This should ensure that operational optimisation is the starting point rather than more capital-intensive schemes. The limit of one day for design nominal retention time should ensure that in the future reservoirs proposed with storage times in excess of this would have to be more stringently justified.

As additional licences are granted competitors will discharge additional sources of water into existing distribution networks. Service reservoirs will prove key junctions for the addition and abstraction of supplies. The design guide highlights the potential water quality problems associated with multiple inlet and outlet arrangements and proposes designs that should be operationally robust.

With increased company and personal liability this increase in complexity will need to be managed.

The work has also empowered the company to take a proactive approach to reservoir management, as opposed to a reactionary approach following a water quality incident.

The service reservoir and serviceability databases can be upgraded to take into account the nominal retention time, probable time to achieve water exchange and propensity for short-circuiting and dead areas.

Due diligence can therefore be carried out in draining down and operating a reservoir believed to have significant dead areas, thereby reducing the risk of a water quality – dirty water incident.

Retrofit optimisation can be scheduled with the annual cleaning programme. Currently cleaning programmes are frequently altered to respond to elevating water quality issues. Which increases the costs and operational resource requirements fro the programme.

Marketing
Conducting the physical modelling at a strategic company WTW site and publicising the programme raised awareness of the project across the business. Scheduling the modelling programme, videoing visualisation tests and encouraging critical management personnel and operations to "buy into" the project and even take hands on

approach during tests was key to acceptance and adoption of the resulting recommendations. As a result key personnel felt a sense of ownership of the finished document and were crucial to ensure its application.

If the research had been conducted in isolation and presented as a finished document then it is possible that it would not have been adopted as a company standard.

By November 2000, 15 specific reservoirs were in a programme to be retrofitted and optimised in line with the design guide recommendations. One new reservoir site was also being designed. Lithium tracer tests were to be conducted post implementation and compared to the predicted model performance.

7 Conclusions & Recommendations for Future Work

7.1 Conclusions

The main conclusions that can be drawn from the work in this thesis have been outlined below.

- The majority of unbaffled reservoirs exhibit predominantly mixed flow characteristics. Network models that assume they exhibit near perfect plug will be prone to significant inaccuracy.
- The small fractions of the reservoir volume that are dead space, or bypassing flow, contribute considerably to water quality issues.
- Service reservoirs can be designed and operated to eliminate dead areas and promote good mixing and water exchange. Performance characteristics can be defined and linked to water quality optimisation.
- Where the appropriate design is used, good water exchange can be achieved rapidly without the requirement to alter the top water level in the reservoir.
- The nature and relative position of both the inlet and outlet are critical in determining the flow pattern in the tank. This consequently determines the mixing achieved, the relative position and volume of dead areas and how robust the performance is with respect to operational changes.
- Existing multiple inlet – outlet tank arrangements and designs where the inlet and outlet are in relative close proximity are prone to large variations in performance under different steady state and transient conditions. This presents a risk to water quality compliance.
- Rectangular tanks with aspect ratios of greater 2:1 are prone to multiple recirculation patterns.
- The limits of applicability of modelling tests should be clearly stated to prevent the application at full scale of a design that is not hydraulically robust for the full range of operational conditions it will encounter.
- The t_{mean} and m-p methods used to estimate dead volumes showed good correlation for steady state flow tests over a wide range of geometries.
- Coefficient of variation measurement is the most appropriate method for qualitative measurement of mixing performance. Placement and number of monitoring points is critical to the reliability and significance of the results.
- Application of empirical mixing models outside the conditions under which they have been derived should be avoided.
- Service reservoir modelling can be used as a means of estimating the concentration of oocysts in the treated water that consumers would have been exposed to during an outbreak

7.2 Further Work

- Further intermittent flow modelling tests are required to adequately assess the implications of intermittent flow on mixing performance
- Series 25 modelling tests need to be corroborated with full-scale plant lithium tracer tests or CFD simulations to determine the apparent discrepancy between calculated dead volumes and flow visualisation assessments.
- Methods of evaluating digital flow visualisation video recordings made during the study could be could be undertaken to provide an unbiased calculation of CV and potentially determine the velocity profile within the tank.
- Further work is required to determine how the m-p model predictions of flow fractions can be related to flow visualisation tests.
- The implications of Coanda effect on mixing and dead volumes should be further evaluated.
- Service reservoir and serviceability databases can be upgraded to take into account the nominal retention time, probable time to achieve water exchange and propensity for short-circuiting and dead areas.

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Standard Operating Protocols for the Monitoring of Cryptosporidium Oocysts in Treated Water Supplies to Satisfy Water Supply (Water Quality) Amendment Regulations 1999 SI No 1524

Water Supply (Water Fittings) Regulations 1999 includes SI No. 1148

The Drinking Water (Undertakings) (England and Wales) Regulations 2000 SI No.1297

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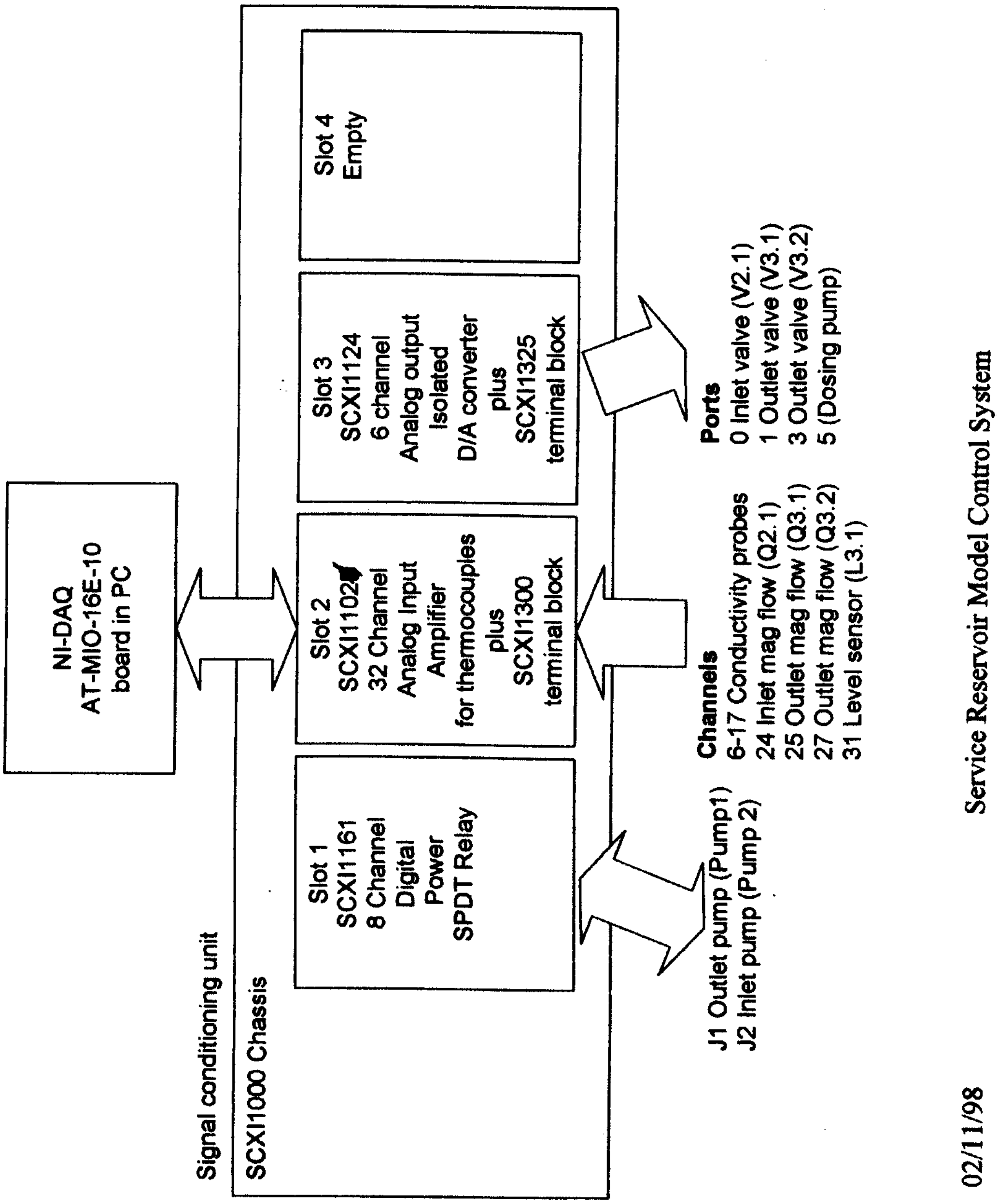
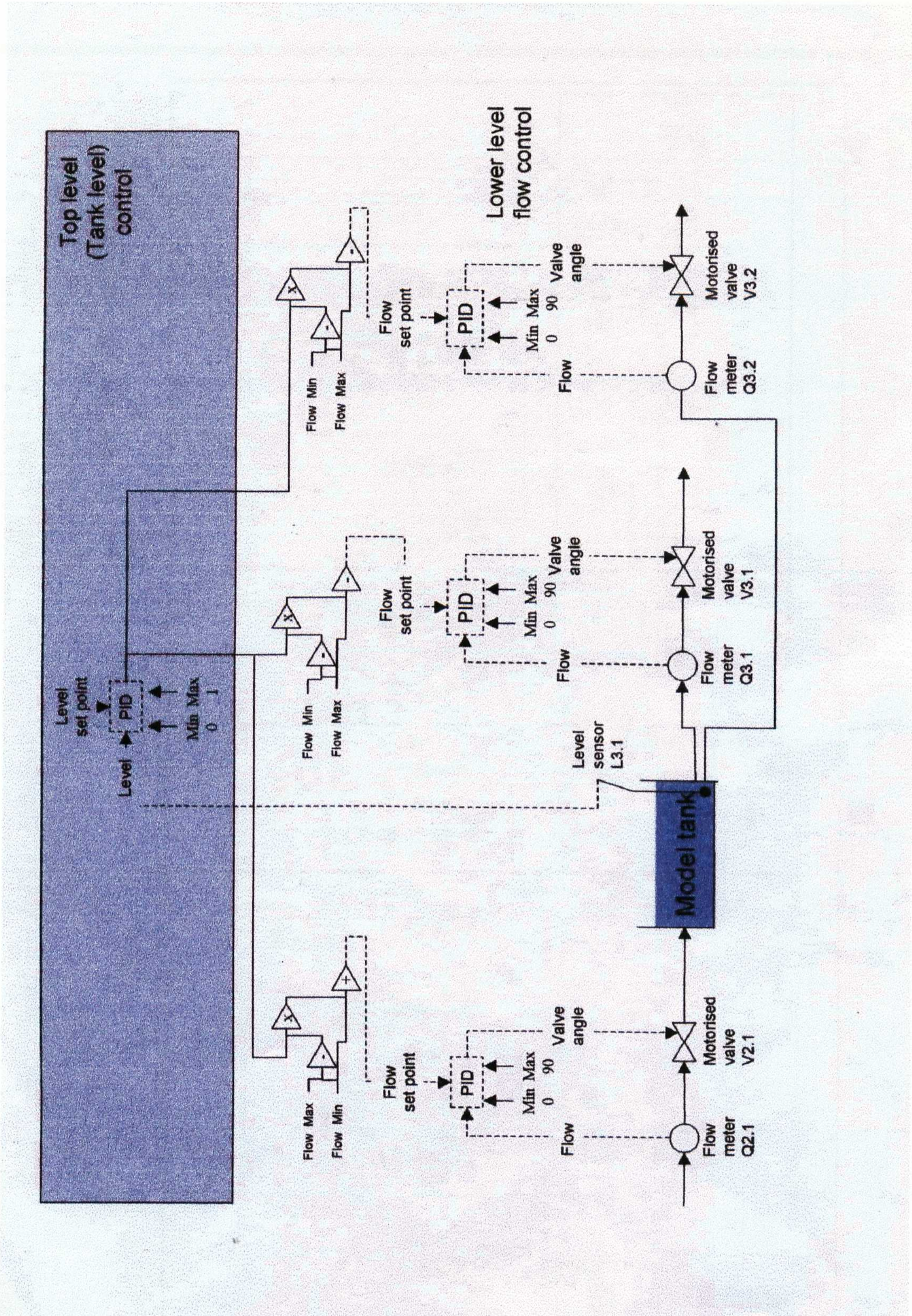
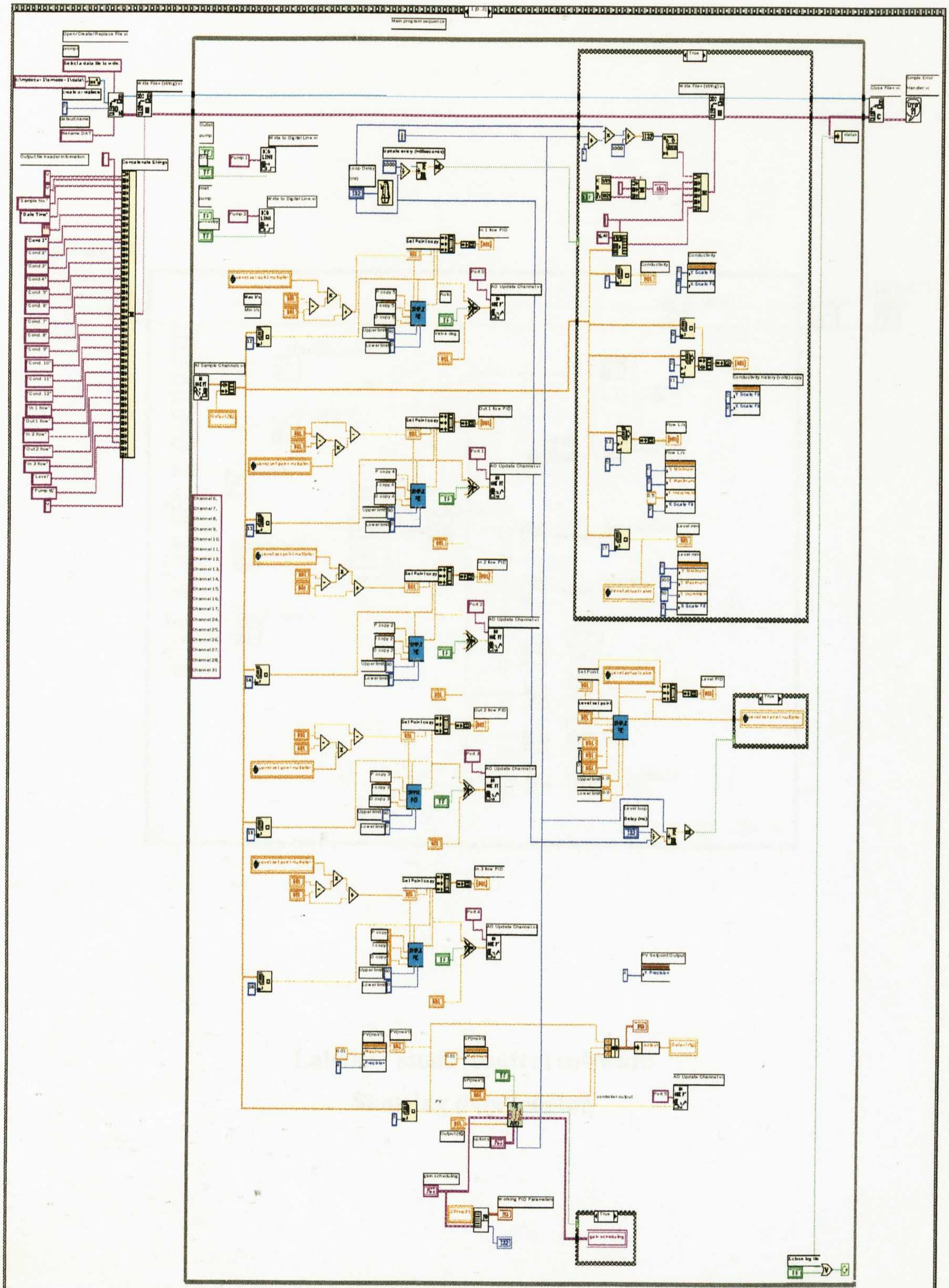


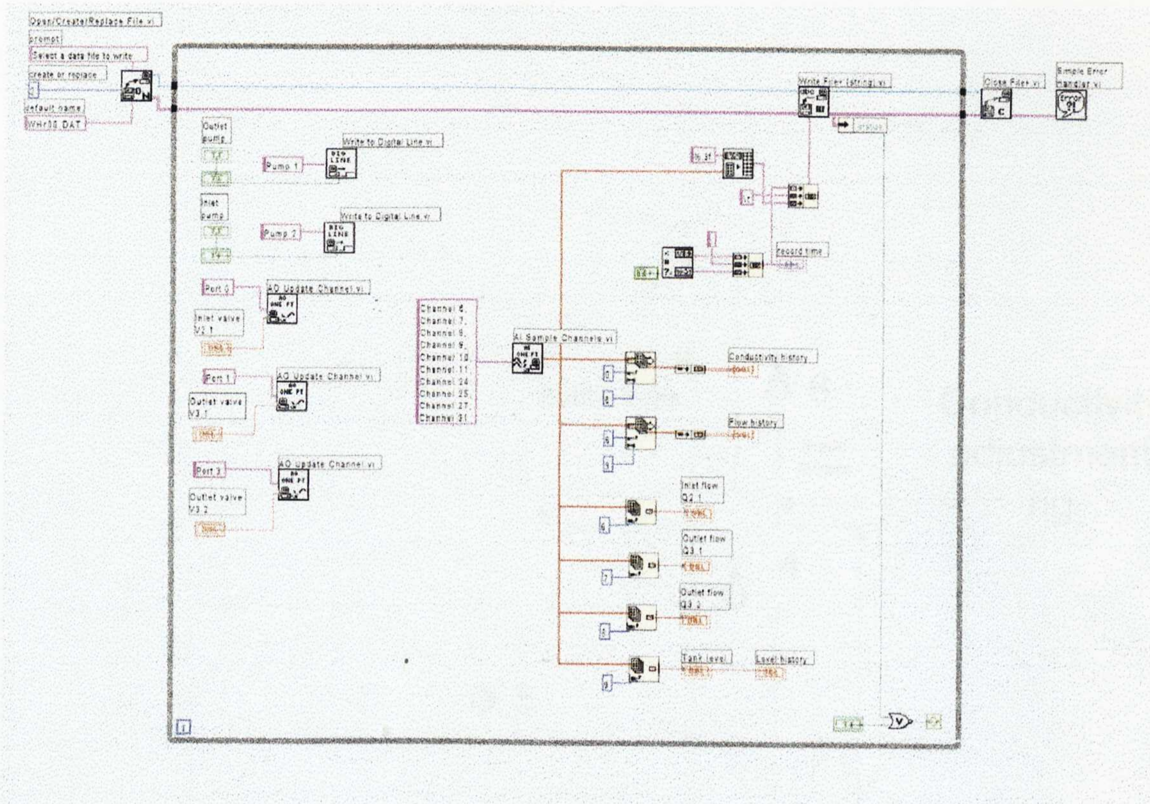
Labview Control System Hardware



Schematic of steady state level control program



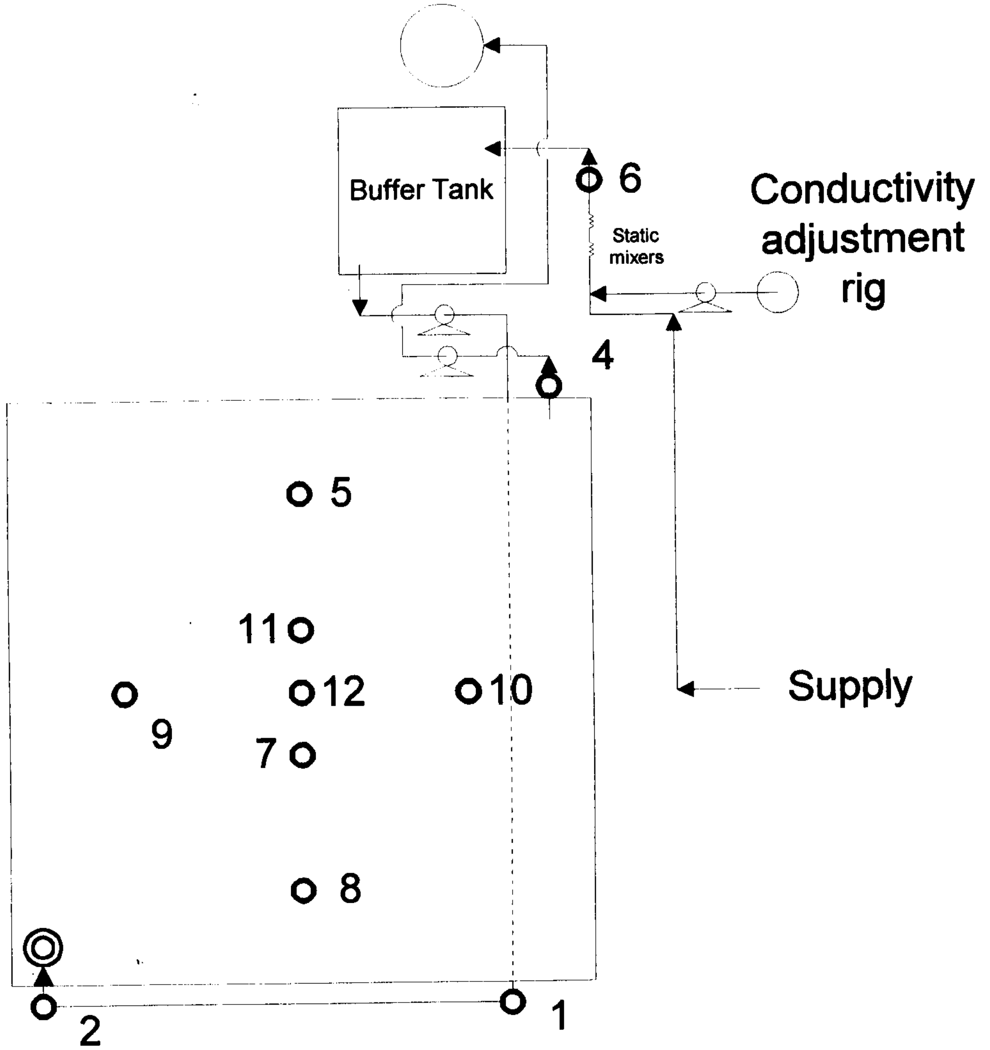
Labview: Model control software showing level control



Labview model control software

Showing data logging

Service Res. Model 1:1



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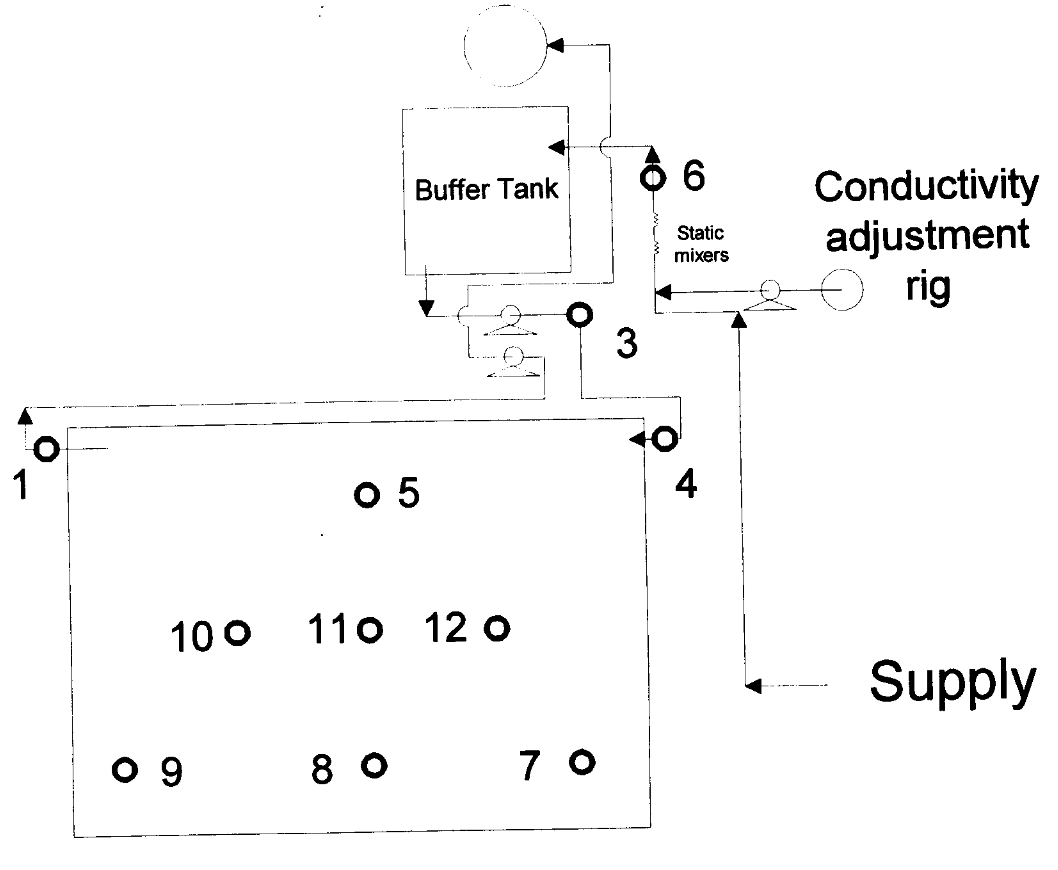

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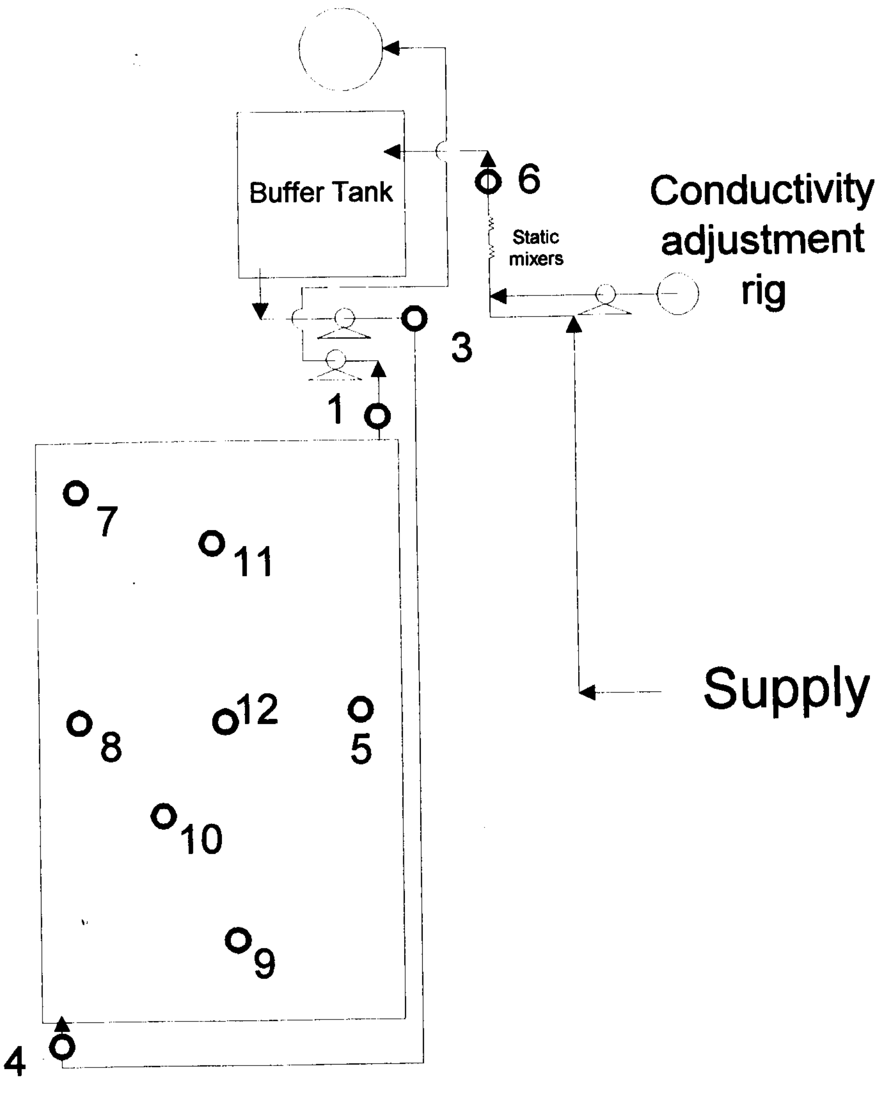
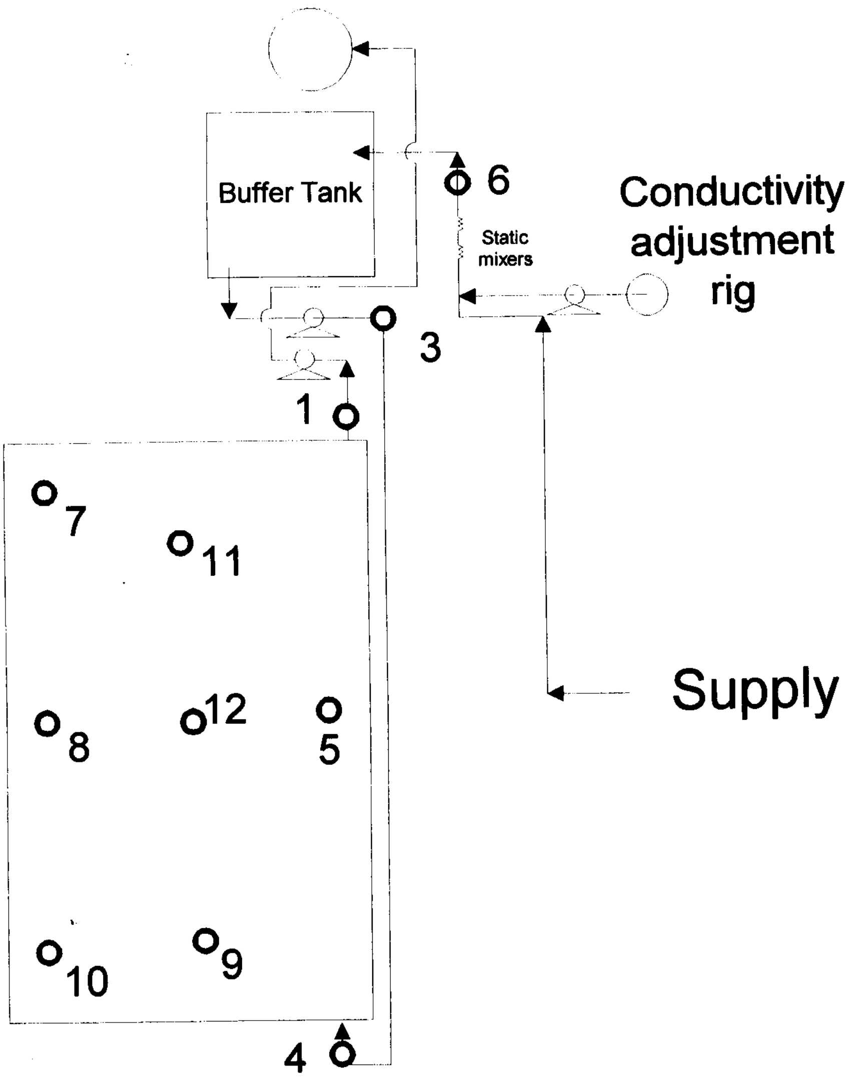


Service Res. Model 2.3:1



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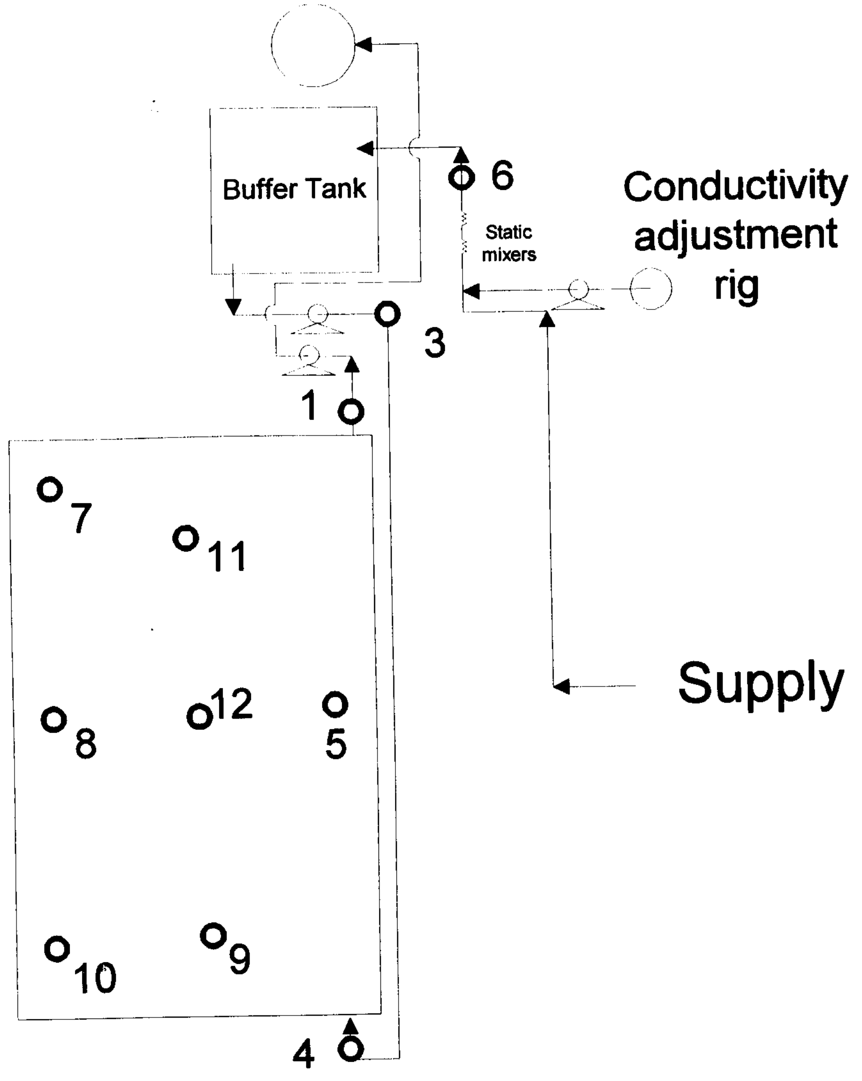
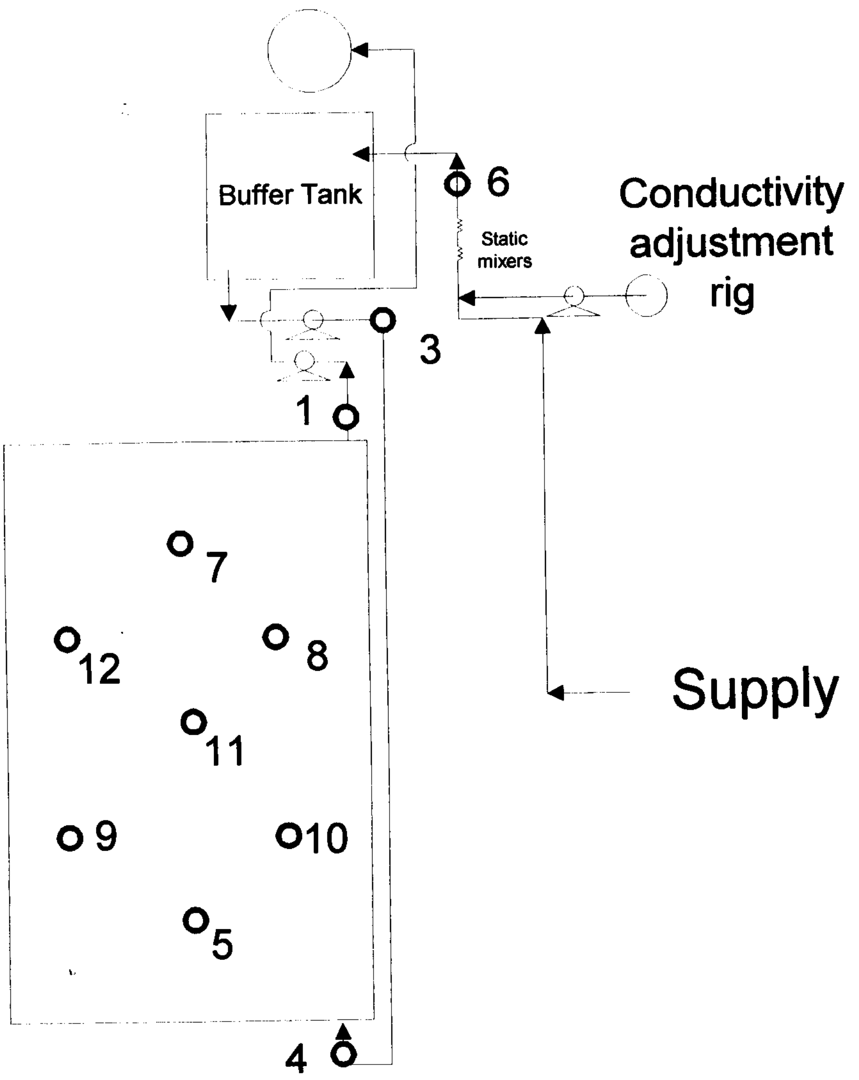


Service Res. Model 3.91:1



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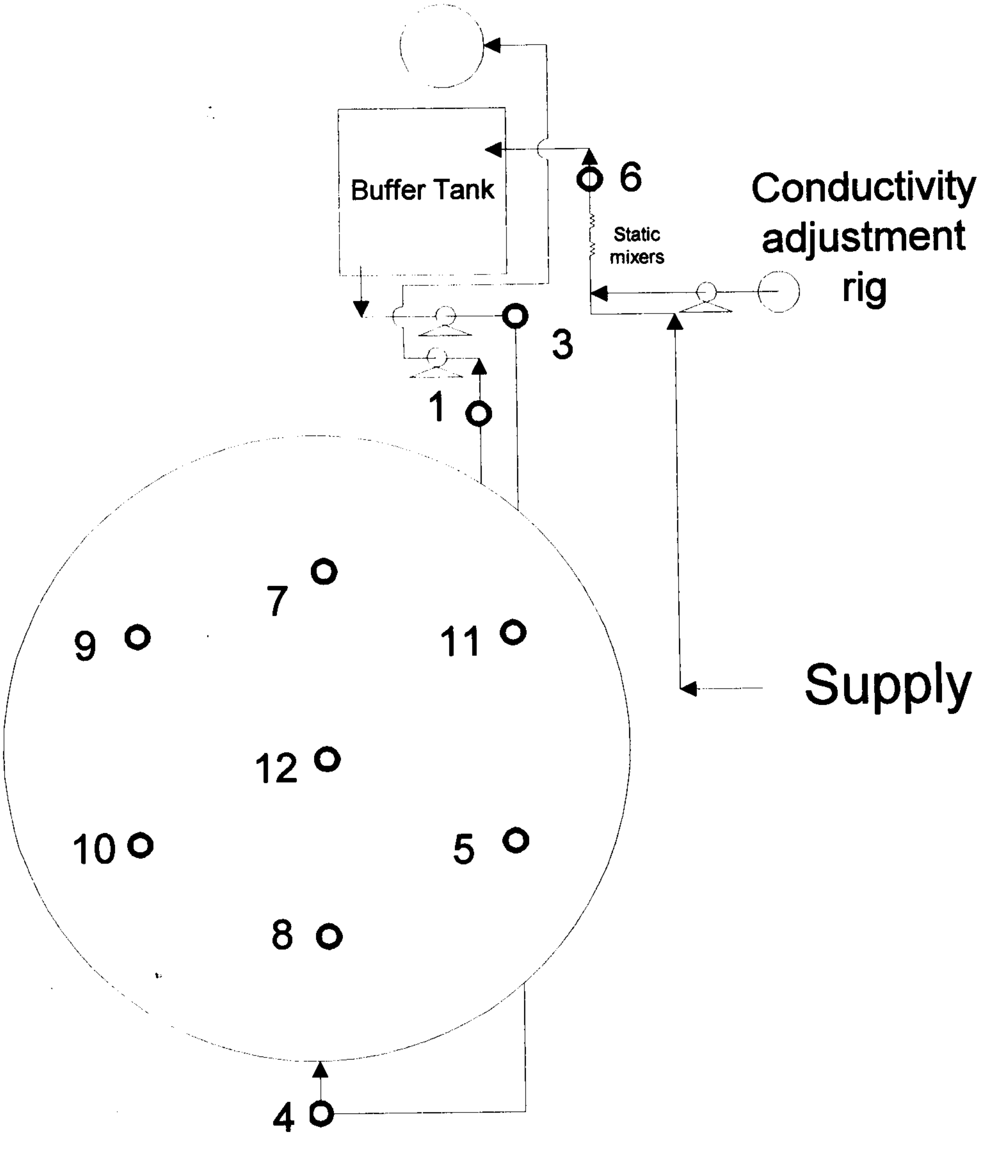


Appendix C1

CASE STUDY 1

Site 1 Treated Water Reservoir
Bacteriological compliance and low chlorine residual

1. Background

The Site 1 reservoir system consists of two circular above ground tanks (*a* & *b*) with storage capacities of 2.5ML and 22 ML respectively.

Reservoir *a* has three 42-inch inlets on one side of the tank, with corresponding outlet pipes of equal diameter on the opposite side of the tank. The combined flow into the tank ranges from 178 to 208 ML/D. The nominal retention time is approximately 15 minutes.

Flow enters reservoir *b* via an 18" branch main that is manifolds to all three incoming mains. The volume of flow entering the tank via this inlet is un-metered. . Tanks *a* and *b* are directly connected via a 39" short length of main, which is effectively a push pull inlet/ outlet. See Figure 1. The nominal retention time in tank *b* was unknown.

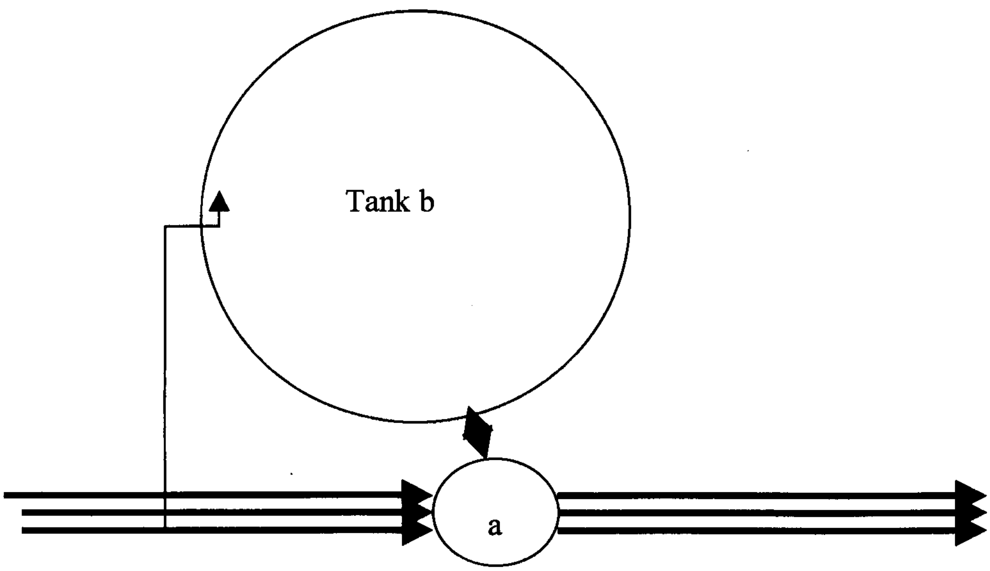


Figure 1. Schematic Site 1

2. Hydraulic Performance of Site 1

The 18-inch inlet enters the tank at base level. A 90 degree -bend has been used to angle the flow parallel to the sidewall. With the 18" inlet operating only , a circumferential jet was established with a quiescent or dead area in the centre. Figure 2.

The flow may pass continuously around the circumference of the tank and then out into tank a. Physical modelling indicated that the central dead volume was between 30 and 40%.

If the flow from the 39 inch inlet from tank a is dominant then a different flow pattern results, Figure 3.

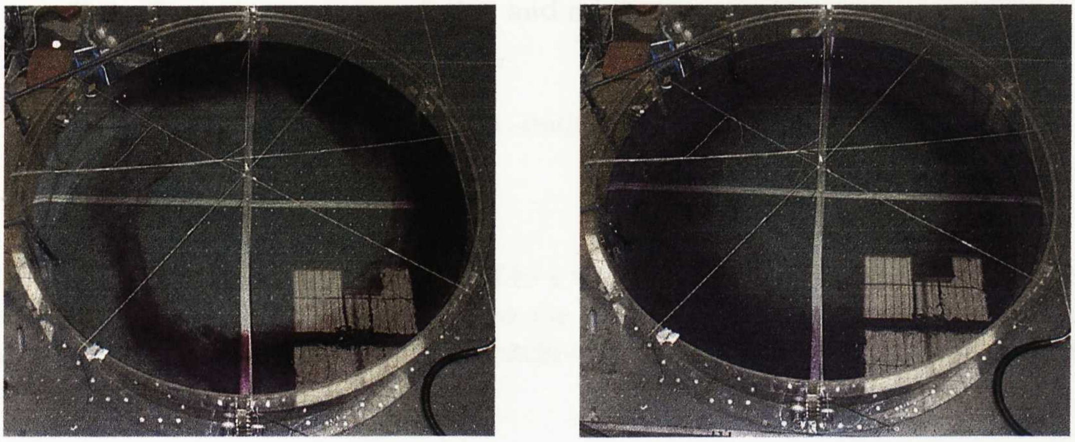


Figure 2. The 18" inlet only operating

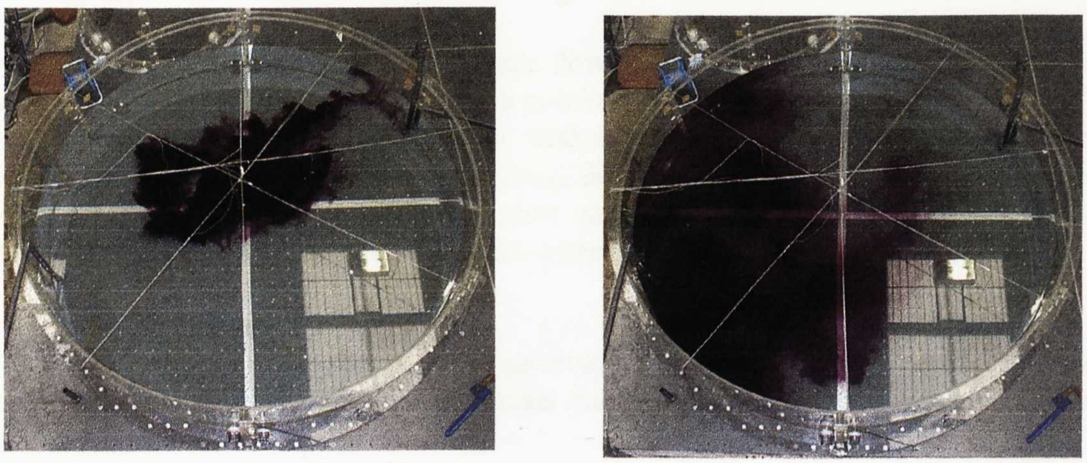


Figure 3: Existing design tank b: dominant flow from 39 inch inlet

Here there is the potential for formation of two dead areas. In this instance dead areas with an estimated combined volume of 13.5 to 24 % are formed in the centre of each circulation. It is anticipated that the pattern in the tank will change between these two dominant patterns as the pressure and flows in the aqueducts change. The most quiescent zone of the tank when the 18 inch inlet flow dominates occurs in the centre. This becomes the area with the highest velocities when the 39-inch main flow dominates. Any settled deposits in the centre of the reservoir will be re-suspended when the 39 inch main acts as an inlet.

This led to a situation with the potential for water to be stored for unquantified lengths of time with no chlorine residual, then be disturbed and released into supply.

It should be noted that the temperature of the stored water could increase significantly as a function of the metal roof and the structure being above ground. Therefore stratification effects were also expected to occur.

3. Retrofits to increase circulation and minimise water age.

Three issues needed to be addressed

- the push pull nature of the inlet(s) –outlet system
- the propensity for dead areas
- the uncontrolled water age.

The design of the existing inlet lent itself to a very simple and effective retrofit solution. The relocation of the outlet pipework to the centre of the tank created a spiral flow pattern, with flow circulating the circumference of the tank and spiralling into the centrally positioned outlet.

This design would not be robust when operated with intermittent flow. The solution to assuring continuous inlet and outlet flow was to throttle the inlet of one of the mains entering tank *a* such that it forced flow through the 18 inch main and into tank *b*.

Measurement of the flow with an ultrasonic flow meter indicated that sufficient flow was passing through the reservoir to ensure a nominal retention time of less than a day. The retrofit option was evaluated on two scaled models of 1.3 and 2.6m diameters respectively. In all cases the short-circuiting flow was eliminated. The estimated dead volumes calculated from steady state tracer tests ranged from 0 to 15%. The flow visualisation tests indicated that dead areas where eliminated.

4. Bacteriological Failures

The compliance sampling point for both reservoirs was within tank *a*. There had been no reported E.Coli failures. This is an important factor in determining the primary cause for failure.

Coliforms that originate via the faecal oral route generally do not survive for very long in the environment. Hence even if they survive disinfection at the WTW their numbers will reduce with age through the distribution system. Their presence at the outlet of service reservoirs would therefore be indicative of animal infiltration and or ingress.

Environmental coliforms however will survive and can multiply within potable water if the conditions are correct. They can multiply at a rate of 1 log every 1.5 to 2 days at a temperature of 10 degrees Celsius. The rate of multiplication in the absence of any disinfection effect would only be nutrient or competition limited.

4.1 Cause of Failure

The coliforms at Site 1 therefore potentially originated from three sources

- **Coliforms which have survived the disinfection process at WTW and recovered within the aqueduct prior to Site 1**

The was considered unlikely as the retention time in the pipeline from WTW to Site 1 was of the order of 12 hours, hence it was unlikely that coliforms would have recovered and multiplied prior to reaching Site 1.

- **Ingress through tank a or b**

This was considered a potential source of contamination.

- **Bacteriological multiplication in tank b.**

The storage time in tank b was excessive, with large bodies of relatively quiescent water with no chlorine residual and significant levels of TOC as a food source. Environmentally derived coliforms originating from route 1 or 2 could therefore be expected to increase in numbers at the rate of 1 log every 1.5 to 2 days until the nutrient supply limited multiplication. Hence a single viable coliform could potentially lead to $1\text{x } 10^{15}$ coliforms due to the length of storage with no chlorine residual (estimated to be in excess of 20 days for complete water exchange) Numbers are unlikely to be as high as this due to nutrient level limitations. However $1\text{x } 10^{6}$ could have been anticipated.

In addition coliforms can colonise the biofilms in the reservoir walls and sediments which could have easily accumulated in the central area of the tank and then been dispersed as the flow pattern changed.

5. Recommendations

- **Provide a chlorine residual in Tank b**
  Temporary chlorination facilities were installed at the site. It was anticipated that ongoing capital schemes would assure the chlorine residual could be maintained to the site in the future.
- **Retrofit Tank b to eliminate the central dead area**
- **Increase the flowrate into Tank b.**
  This was achieved in a stepwise manner to minimise the risk of an upstream burst.
- **Repair the roof to Tank b reduce the risk of any future ingress.**

Full scale implementation was due November 2000.

CASE STUDY 2

Site 2 Treated Water Reservoir: Periodic iron compliance issues

1. Site 2 Design and basic performance

Reservoir 2 comprises a twin tank with symmetrical compartments, separated by a 2/3 height wall. Each compartment has a width of 61.7m and a length of 91.4m giving it and aspect ratio of 1.48:1. The maximum depth was reported to be 6.93m. The inlet to each compartment was a 1.2m diameter horizontal straight pipe at base level that traversed the length of the tank discharging into the opposite wall. The outlet was positioned in a sump adjacent the inlet. See Figure 1.

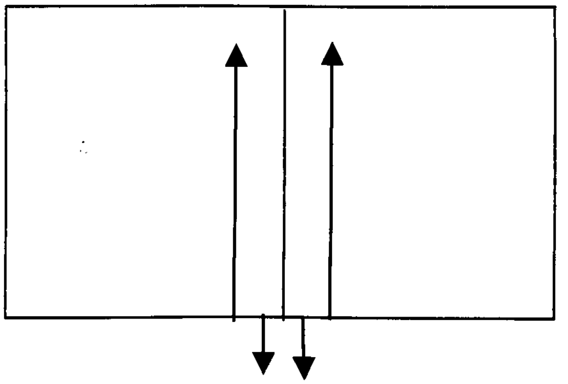


Figure 1: Schematic of Site 2 Service reservoirs

The reservoirs receive water from Site 2 WTW. In the past the reservoir has had an intermittent problem with high iron levels even though the water supplied to the reservoir was in compliance for iron. The reservoir was taken out of service and cleaned, directly after cleaning the iron levels improved and then subsequently began to elevate again. The water entering the reservoir has typically an iron concentration of 50ug/l approximately ¼ MAC.

2. Physical Modelling Study

A single compartment of the reservoir was modelled. The results were then applied to the symmetrical twin compartment. Although there is the potential for crossover flow between the reservoir halves at maximum top water level. The nature of the inlet indicated that the highest velocities would occur across the floor of the tank and therefore any cross over flow at high water level was considered to be secondary.

The model was initially operated at steady state to establish the baseline performance. The design was then challenged by extremes of operation (intermittent flow, rapid level changes) to ensure that the design is robust.

2.1 Existing design performance

The inlet pipe discharged directly into the opposite wall and the flow split into two separate streams. One stream was channelled by the inlet pipe, and short circuited to the outlet. It then proceeded around the periphery of the tank forming a circulation. The second jet only travelled a short distance before turning to join the main circulation. The resulting dominant flow pattern in the tank was therefore a strong peripheral circulation with a significant quiescent area in the centre of the tank. The performance varied between a completely mixed tank and a tank with a estimated 10 percent central dead area.

The combination of high chlorine residuals and pH are conducive to the formation of particulate iron from any soluble. The quiescent area in the centre of the tank provides an ideal location for deposits to settle. Operational changes such as increases in demand or significant changes in inlet flow or level were sufficient to change the flow pattern slightly such that it is feasible that deposits would be entrained in the flow, resulting in spikes of iron at the outlet of the reservoir. The modelling results correlated with the observed pattern of decline in iron spikes after cleaning with subsequent increases with time back in service.

3. Recommendations

The two options considered are discussed below. The objective for both options was to assure that the twin reservoirs were completely mixed with minimal zones for solids depositions.

Option 1:

This required extension of the inlet pipe to the end of the tank and up the opposite wall, terminating in an upturned bellmouth above TWL. The final geometry would be an inlet and outlet directly opposite each other. There were underlying concerns about the potential for increased channelling of the inlet flow due to the placement of the inlet pipe in the base of the tank. In addition there were concerns as to the head availability from the WTW. With this arrangement there is still the potential for dead areas in the centre of the tank. Hence this option was not the preferred option.

Option 2

It was proposed that the existing inlet pipe be terminated as it entered the tank. The removed pipe section could then be utilised to extend the outlet to a position within the centre of the tank. Thus when inlet and outlet were operating a spiral flow would be created around the periphery, spiralling into the centre. This was perceived to be a better solution.

It was noted that there was an inherent risk in this approach. If the reservoirs were not operated with continuous inlet and outlet flow, then the performance would deteriorate. In these circumstances the actual performance could be anticipated to be worse than if the asset were not refurbished. Although this mode of operation was not considered to be a high risk as the reservoir took all the flow from a strategic WTW.

It was evident that in this instance even small degrees of deposition and relatively small dead areas were contributing to quality issues. Hence assuring a uniform minimum velocity across the base of the tank was key to minimising deposition. Operational optimisation routes such as reducing the tank level and directly all the flow through a single tank were considered. In addition optimisation of the WTW was recommended to further reduce iron levels leaving the treatment works.

CASE STUDY 3
Site 3 Treated water Reservoir
Erratic chlorine residuals and THM non compliance

1. Introduction

At Site 3 there were two service reservoirs, *a* and *b*. Service reservoir *b,* the larger reservoir was the subject of this study. The site and the two-system reservoir network were associated with increases in THM's and poor levels of control for final chlorine residual.

Reservoir *a*, was a rectangular push pull tank with two inlet / outlets, the flow in and out of which was uncontrolled.

Reservoir *b* was an odd geometry tank with internal significant benching on one side. The single inlet discharged into a wall, which acted as an impingement plate, splitting the flow. Two outlet pipes delivered re-chlorinated water to separate distribution zones. Both outlet could be combined with uncontrolled flow from reservoir *a*.

A model of the existing reservoir *b* was trialed under various inlet, outlet and relative flow ratio conditions. Several retrofit solutions were trialed. A total of 67 individual tests were conducted to establish the baseline performance of the existing tank and the efficacy of potential retrofits under a wide range of potential operating conditions.

1.1 Model Scaling

The geometric scaling ratio of the model was very large 68.3 : 1, which meant that the model operating depth was very shallow, typical depths of <100mm. At these depths the frictional forces due to the side walls and the base of the tank were more dominant than the equivalent forces on the full scale. Hence even the presence of microscopic bubbles on the base and the walls of the model could influence the flow pattern.

To overcome this effect the model was operated at increased flowrates and then the results adjusted accordingly. Operating at larger flowrates could result in the formation of unrealistic surface effects such as waves. In most cases this has been overcome by minor modifications to the inlet.

Use of small physical models for large water bodies is not uncommon and these effects are seen when models of rivers etc. are run. In these instances the vertical scale (depth) is often reduced so that the models are run at increased depths to minimise these effects. Advantage was therefore taken of the potential to run the model at increased depths. This produced more consistent results.

2. Results

2.1 Existing tank model: (Vertical scale 68.3:1, Horizontal scale 68.3:1)

The flow path through the tank proved to be heavily dependant upon the operating level. Two dominant flow patterns were established with a transient phase as the flow path changed from one pattern to the other.

At water depths of approximately 4.3m full scale (63mm on the model) and below, the incoming flow split equally and formed two jets. One jet travelled along the straight side of the tank and reached outlet 2 before progressing around to outlet 1. The other jet travelled along the expanding side of the tank and then began to turn inwards. Hence the initial flow pattern resembled the letter 'b' then progressed into a figure of '8'type of pattern. See Figure 1. This resulted in two re-circulating cells in the tank, one small, and one large with a large central quiescent area. These operating depths were below the level of the side benching.

At levels of 4.8 m full-scale and above (70mm on the model) the incoming flow again split equally and formed two jets. One jet travelled along the expanding side of the tank and reached outlet 1 typically before outlet 2. The second jet travelled along the straight side of the tank and then begins to turn inwards. Hence the initial flow pattern resembled the letter 'd' then progressed into a figure of '8'type of pattern. Figure 2. Again this resulted in two re-circulating cells , one small, and one large with a large central quiescent area.

Both flow patterns were consistent and repeatable. The distance that the jet travelled before turning inwards in each case was a function of the inlet flowrate. The switch from one flow pattern to the other was heavily dependent upon the water level in the tank. Although the flow path was different in each case, both dominant patterns resulted in large central quiescent zone and a re-circulating area close to the inlet. A transient phase existed as the flow switched between one flow pattern and the other. This is likely to result in periodic disturbances of the large central area of the tank.

The dramatic change in the flow pattern was not anticipated at the outset of the modelling. It was initially thought that this could be an artefact of the shallow operating depth of the model. Therefore the trials were repeated at twice the depth, with the increased scale benching, inlet and outlet arrangements.

Subsequently it was shown that the results obtained at low level (< 4.3 m) are supported by operator observations and by recent lithium tracer test results. See Figure 3 and Figure 4.

2.2 Increased depth model (Vertical scale 34.15:1, Horizontal scale 68.3:1)

The results obtained with the increased depth model were in line with those of the shallower depth model but proved more consistent. The dominant flow pattern was typically that depicted in Figure 2. During each tests the ratio of t_0/T for each outlet was determined. It varied from 0.21+/-0.09 to 0.6 % +/- 0.1for Outlet 1, to 0.14 +/- 0.2 for Outlet 2. This degree of variation was a function of the changing flow pattern in the tank.

So the leading edge of the flow short circuited to the outlets, while some of the flow remained in the tank for a much greater time. The dispersion index of the existing was determined to be 16.19 +/- 7, CV was calculated during step tests to be poor 0.43.

The fact that one of the outlets generally takes three times the flow of the other outlet did not have a large impact on the bulk flow pattern.

3. Conclusions and Implications

The implications of these results are that there was a central area in the tank with water of much higher age. Rapid changes in outlet flowrate, which were common on this site resulted in some of this water being passed into distribution, which contributed to the rapid fluctuations in chlorine residual.

4. Retrofit Options

The primary objective was to ensure that the tank behaved in a known consistent manner, irrespective of the operational regime i.e. variable inlet / outlet flowrate and top water level and that significant dead areas should be eliminated.

Two main routes considered for optimisation of the tank were to turn the tank into either a mixed or plug flow tank. The plug flow option was considered as a function of the irregular geometry.

4.1 Plug Flow

After a thorough evaluation a plug system was ruled out because of the extensive baffling that would be required. In addition a plug flow system would result in a greater loss of chlorine residual across the tank.

4.2 Mixed tank

This was the favoured option tank as the tank received a relatively consistent and continuous inlet flow with some degree of continuous if variable outlet flow.

It was proposed that the momentum of the inlet flow be utilised more effectively to mix the contents of the tank. This was achieved by modification to the inlet to force the flow to take one path around the tank.

One retrofit outperformed the other potential solutions. It eliminated dead areas within the tank and proved to be robust over an extreme range of operational conditions.

The final coefficient of variation was much less and the time to achieve better mixing was significantly reduced.

5. Recommended Retrofit

The left hand side of the inlet (parallel to the straight side of the tank) was blocked off completely forcing flow to circulate around the expanded side of the tank. Both outlet pipes were relocated centrally in the tank, close to the widest expansion of the tank. Shown schematically in Figure 5. A minimum distance was maintained between the two outlet pipes to prevent vortexing. This modification forced the inlet flow to form a strong recirculating flow around the periphery of the tank, the flow circled the circumference of the tank twice then spiralled into the central outlets. In-coming flow was directly mixed with recirculating flow.

Typical flow patterns are shown in Figure 6. And a typical RTD curve is shown in Figure 7. This can be compared with a lithium RTD for the existing tank Figure 8.

The minimum retention time of the tank was not altered dramatically by the modification however the maximum water age was significantly reduced. The dispersion index changed from 16.6 +/- 9, to 5.3 +/-0.5 for Outlet 1 and 6.6 +/-1 for Outlet 2. The performance also improved when both outlets were abstracting the same flow.

It was anticipated that erratic chlorine residuals would be reduced. The reduction in maximum water age was anticipated to result in a reduction in THM formation. The retrofit has been applied at full scale. However the author is no longer in a position to gain access to the results.

Figure 1.
One jet travels along the straight edge, the other turns inwards and re-circulates around the inlet. Flow reaches Outlet 2 before Outlet 1

Figure 2.
Jet travels along expanded edge, reaches Outlet 1 before Outlet 2.
Flow begins to recirculate towards centre, leading jet approaches Outlet 1.

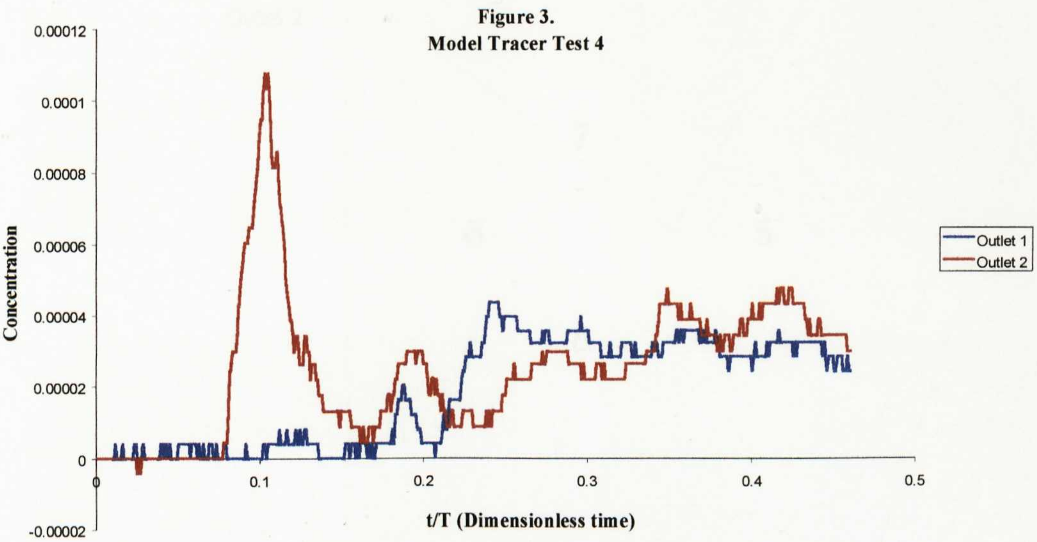


Figure 3 - Model Tracer Test 4

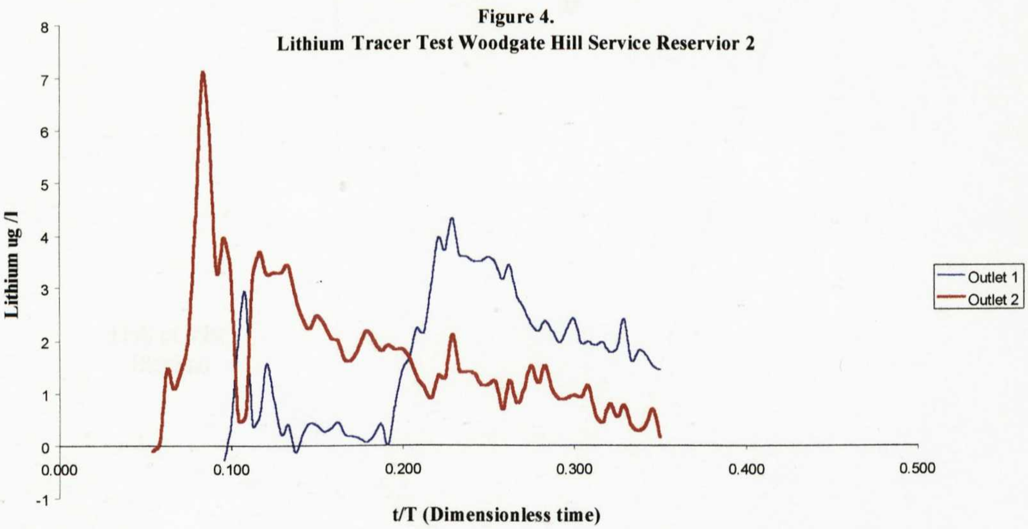


Figure 4 – Lithium Tracer test

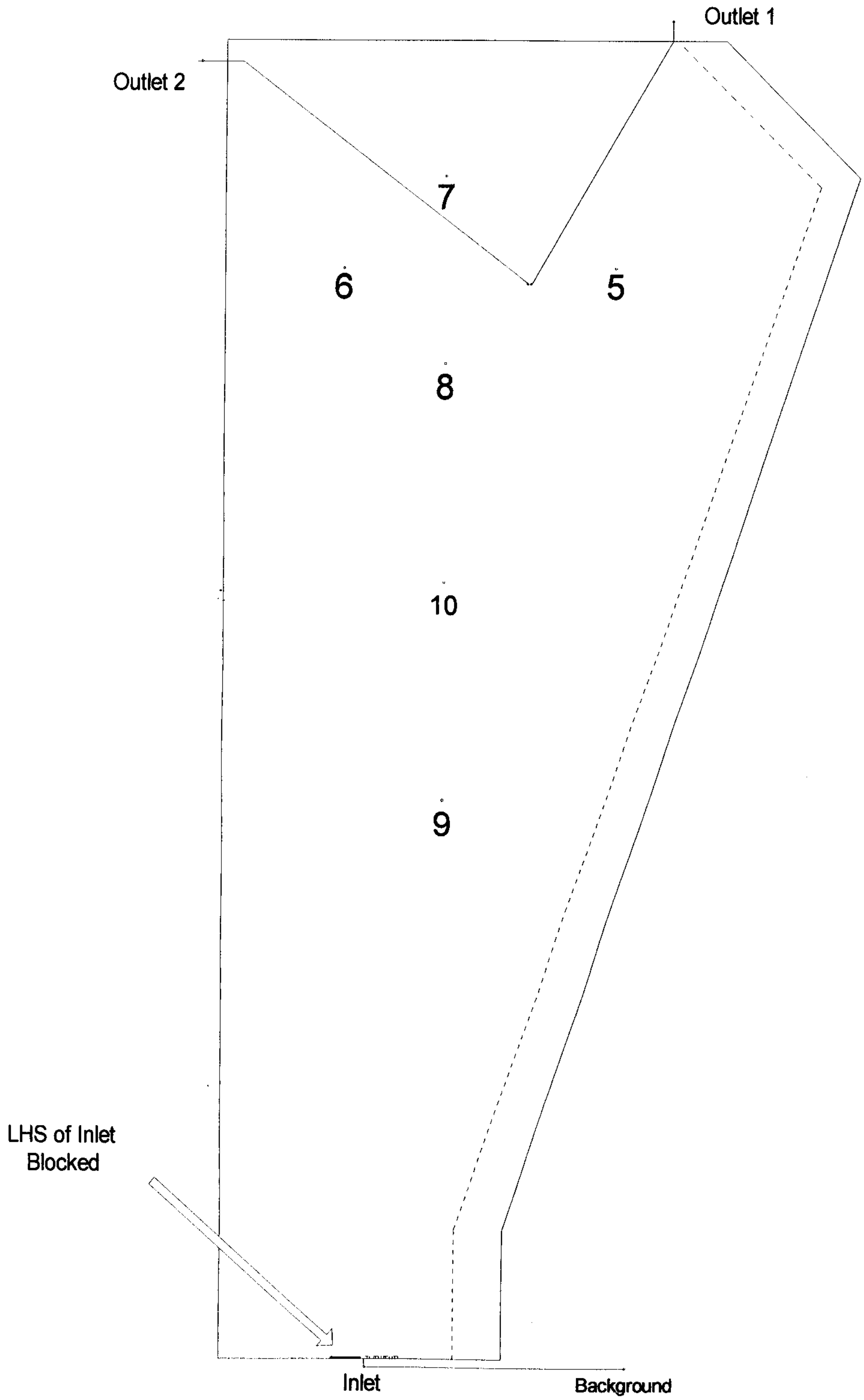


Figure 5: Schemmatic of Retrofit Layout Showing conductivity probe positions
N.B. Not to Scale

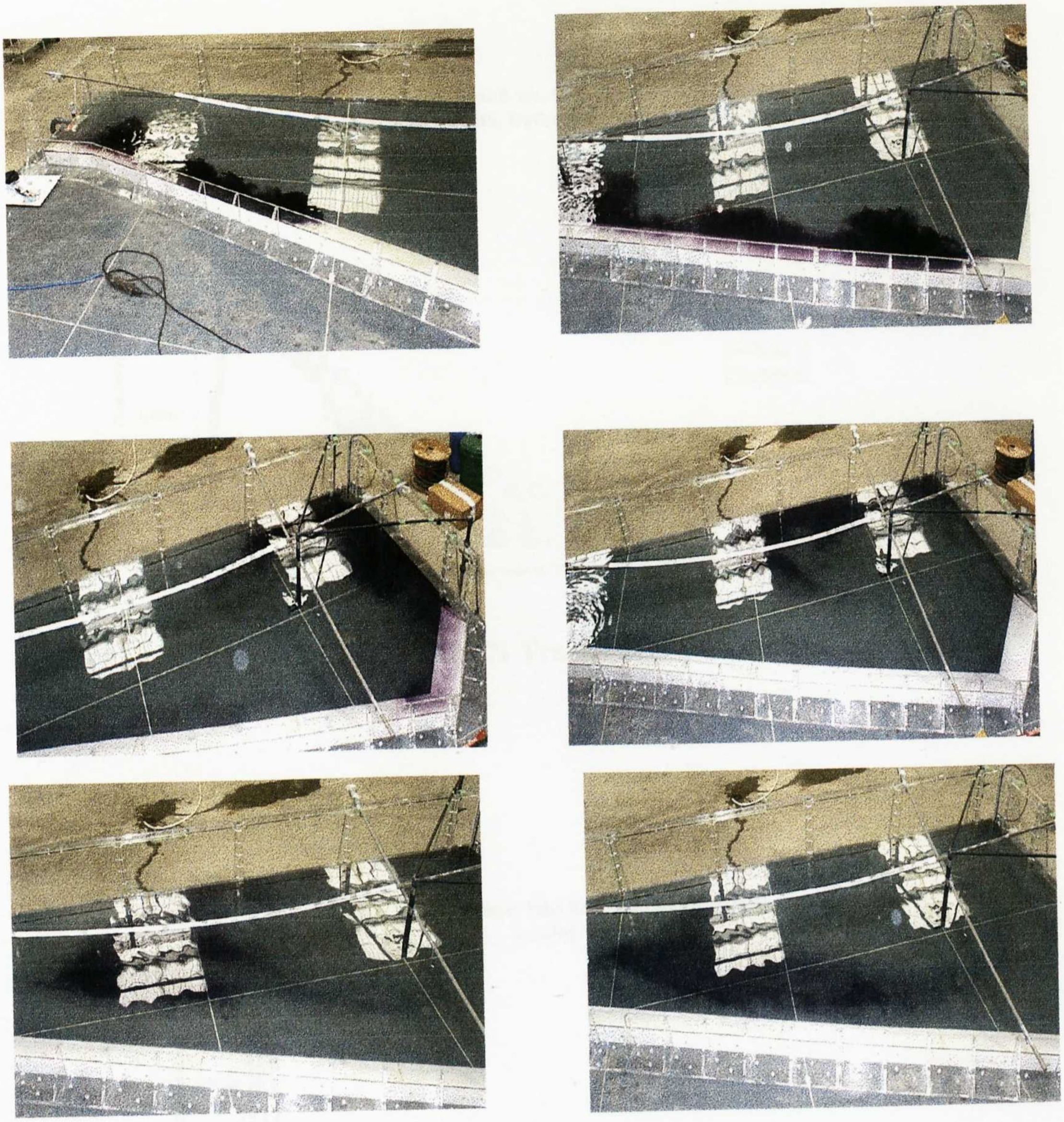


Figure 6: Retrofit showing spiralling flow pattern

After second circulation flow begins to spiral into the centre

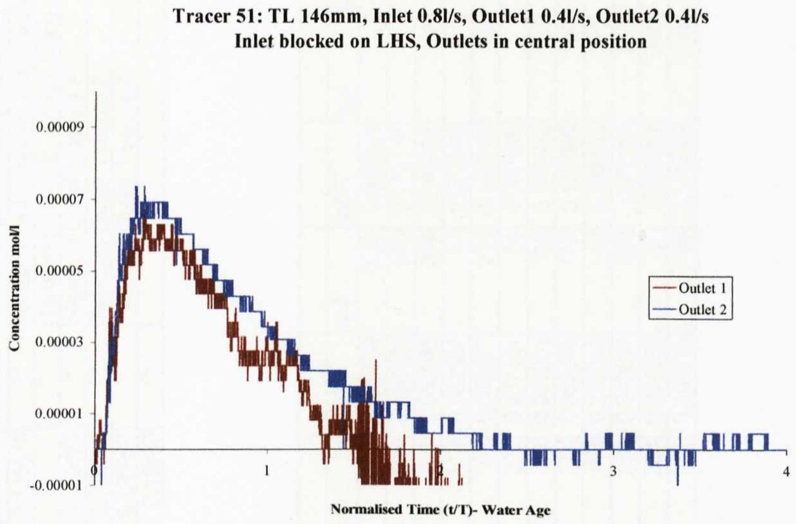


Figure 7: Tracer 51

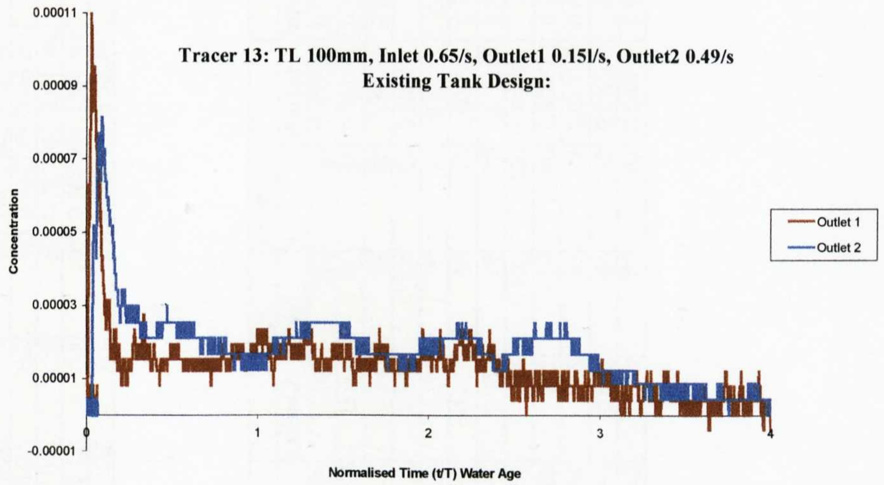


Figure 8: Tracer 13

Low Benching	Date	Inlet Flow	Outlet 1	Outlet 2	Level	Volume	retention	to1	to1/T	to2	to2/T	Inlets & Outlets (Original Configuration)	
Dye Tests	10/12/98	0.138	0.036	0.098	83	0.802605	5815.976	1325	0.22782	730	0.125516	""	repeat of test 2, system left to settle for 30 m
	05/11/98	0.24	0.04	0.16	100	0.973783	4057.427					""	Tank was filling up, straight along straight sid
	08/12/98	0.26	0.07	0.2	82	0.792535	3048.213	198	0.06496	505	0.165671	""	Reached Outlet 1 before 2
	09/12/98	0.396	0.1	0.28	82	0.792535	2001.352	95	0.04747	242	0.120918	""	Reached Outlet 1 before 2
	08/12/98	0.52	0.12	0.4	81	0.782466	1504.742	85	0.05649	190	0.126267	""	Reached Outlet 1 before 2
	07/12/98	0.13	0.03	0.1	85	0.822743	6328.794	1920	0.30338	1240	0.19593	""	

Low Benching																	
	Dosed mls					start	Finish			Theoretical retention							
Tracer		Date	Inlet Flow	Outlet 1	Outlet 2	Level		Volume	Volume 2	retention		to1	to1/T	to2	to2/T	t_{10}1	t_{50}1
1	5	15/12/98	0.131	0.025	0.103	82	80	0.792535	0.772397	6049.89	*5973.024*	3162	0.522654	1210	0.200004		
2	5		0.261	0.059	0.208	81	80	0.782466	0.772397	2997.95	*2978.665*	254	0.084724	510	0.170116		
5*	5		0.496	0.129	0.391	89	86	0.86302	0.832813	1739.96	*1709.509*	105	0.060346	244	0.140233	126	564
4*	5		0.52	0.12	0.392	61	61	0.580718		1116.77		114	0.102081	87	0.077904		
3*	5	16/12/98	0.53	0.126	0.375	76	76	0.73212	0.73212	1381.36	*1381.358*	91	0.065877	211	0.152748	105	331
6	5		0.643	0.14	0.487	63	73	0.600831	0.701912	934.419	*1013.019*	222	0.237581	84	0.089895		
8*	5		0.65	0.149	0.482	76	79	0.73212	0.762328	1126.34	*1149.575*	78	0.069251	165	0.146492	103	463
7*	5		0.653	0.154	0.48	100	105	0.973783		1491.24		79	0.052976	182	0.122046	160	1167
9	5		0.784	0.199	0.6	59	60	0.560673	0.570687	715.144	*721.5308*	153	0.213943	142	0.198561	310	826
10	5		0.794	0.194	0.6	65	72	0.621012	0.691842	782.131	*826.7348*	266	0.340096	173	0.22119	387	1161
11	5		0.796	0.196	0.585	64	140	0.610913	1.376554	767.479	*1248.409*	224	0.291865	81	0.10554	345	843
62	17	02/06/99	0.8	0.2	0.6	61	63	0.580718	0.600831	725.898	*738.4683*	77	0.106076	84	0.115719	145	304

Tracer	Dose	Date	Inlet Flow	Outlet 1	Outlet 2	Level		Volume	Volume 2	retention		to1	to1/T	to2	to2/T	t_{10}1	t_{50}1
High benching																	
Inlets & Outlets (Original Configuration)																	
12	5	13/01/99	0.654	0.16	0.472	129	135	1.231921	1.292669	1883.67	*1930.115*	123.00	0.065298	279	0.148115		
13	5	14/01/99	0.65	0.157	0.49	100	103	0.942628	0.972223	1450.2	*1472.962*	116	0.079989	163	0.112399	167	1565
14	5	14/01/99	0.66	0.157	0.501	182	194	1.766437	1.887269	2676.42	*2767.959*						
15	5	15/01/99	0.652	0.16	0.485	114	114	1.081393	1.081393	1658.58	*1658.578*	107	0.064513	238	0.143496		
16	5	15/01/99	0.673	0.161	0.49	138	130	1.323158	1.242025	1966.06	*1905.782*	142	0.072226	277	0.140891	167	376
17	5	27/01/99	1.0195679	0.258178	0.782305	122		1.161436		1139.15		62	0.054427	147	0.129044		
18	5	29/01/99	1.2566716	0.283776	0.971552	128		1.221827		972.272		56	0.057597	123	0.126508	64	158
19	5	01/02/99	1.2494389	0.648824	0.642653	126		1.201662		961.761		47	0.048869	110	0.114373	51	133
20	5	04/02/99	1.0225372	0.788598	0.251949	123		1.17148		1145.66		66	0.057609	138	0.120455	81	287
21	5	04/02/99	1.0283964	0.51885	0.521284	122		1.161436		1129.37		53	0.046929	139	0.123078		
22	5	09/02/99	0.8	0.2	0.6	159	157	1.534844	1.514705	1918.55	*1905.968*	122.00	0.06359	319	0.166271		
23	10	12/02/99	0.8	0.2	0.6	160	159	1.544913	1.534844	1931.14	*1924.848*	166	0.08596	375	0.194186	268	1021
56	15	29/04/99	0.8	0.2	0.6	148		1.424081		1780.1		192	0.107859	295	0.165721	229	581
57	15	30/04/99	0.8	0.2	0.6	142		1.363666		1704.58		107	0.062772	247	0.144904		
59	15	04/05/99	0.8	0.2	0.6	100	102	0.942628	0.962349	1178.29	*1190.611*	132	0.112027	245	0.207929	195	817
60*	15	04/05/99	0.8	0.2	0.6	102	101	0.962349	0.952485	1202.94	*1196.771*	83	0.068998	142	0.118044		
61	15	04/05/99	0.8	0.2	0.6	147		1.414012		1767.52		123	0.069589	321	0.181611	162	467
Inlet blocked on RHS, Outlets (Original Configuration)																	
24	10	16/02/99	0.8	0.2	0.6	160	160	1.544913	1.544913	1931.14	*1931.141*	422	0.218524	140	0.072496	452	481
25	10	17/02/99	0.8	0.2	0.6	123	124	1.17148	1.181532	1464.35	*1470.633*	91	0.062144	45	0.03073	105	329
Inlet cascade removed, Outlets (Original Configuration)																	
38	10	26/03/99	0.8	0.2	0.6	145		1.393874		1742.34		248	0.142337	301	0.172756	361	920
Inlet blocked on LHS, Outlets in central position																	
47	10	12/04/99	0.8	0.4	0.4	146	150	1.403943	1.44422	1754.93	*1780.102*						
48	10	14/04/99	0.77	0.42	0.41	149	118	1.434151	1.121346	1862.53	*1659.414*	76	0.040805	201	0.107918	292	815
49	10	20/04/99	0.8	0.4	0.4	141	145	1.353596	1.393874	1692	*1717.169*	60	0.035461	66	0.039007		
50	30	21/04/99	0.8	0.4	0.4	151	154	1.454289	1.484497	1817.86	*1836.741*	212	0.116621	225	0.123772		
51*	15	21/04/99	0.8	0.4	0.4	146	142	1.403943	1.363666	1754.93	*1729.755*	154	0.087753	178	0.101429	354	939
52*	15	22/04/99	0.8	0.4	0.4	150	148	1.44422	1.424081	1805.27	*1792.688*	139	0.076997	130	0.072011	263	612
53	15	26/04/99	0.6	0.3	0.3	148	145	1.424081	1.393874	2373.47	*2348.296*	134	0.056457	131	0.055193		
55	15	28/04/99	0.8	0.2	0.6	105	107	0.991995	1.011802	1239.99	*1252.373*	89	0.071775	92	0.074194	150	424

Step Tests: Salt 2133.3g/ 60 Litres, Probe Calibration																	
26	**10/Sec**	24/02/99	0.8	0.2	0.6	160	170	1.544913	1.645606	1931.14	*1994.074*	372	0.192632	153	0.079228		**Inlets & O**
27	**4/Sec**	25/02/99	0.8	0.2	0.6	159		1.534844		1918.55		9	0.004691	41	0.02137		**""**
28	**4/Sec**	02/03/99	0.8	0.2	0.6	190	198	0.942628	1.927546	1178.29	*1793.859*	298	0.25291	321	0.27243		**Inlet block**
29	**4/Sec**	02/03/99	0.8	0.2	0.6	100	102	0.942628	0.962349	1178.29	*1190.611*	395	0.335233	384	0.325897		**""**
30	**4/Sec**	04/03/99	0.8	0.2	0.6	145	150	1.393874	1.393874	1742.34	*1742.342*	194	0.111344	196	0.112492		**""**
31	**4/Sec**	05/03/99	0.8	0.2	0.6	190	200	1.846992	1.947684	2308.74	*2371.672*	211	0.091392	211	0.091392		**Inlet block**
32	**4/Sec**	05/03/99	0.8	0.2	0.6	100	106	0.942628	1.001894	1178.29	*1215.326*	127	0.107784	133	0.112876		**""**
33	**4/Sec**	08/03/99	0.8	0.2	0.6	146	151	1.403943	1.454289	1754.93	*1786.395*	138	0.078636	142	0.080915		**""**
34	**4/Sec**	10/03/99	0.8	0.2	0.6	102	110	0.962349	1.041575	1202.94	*1252.453*	197	0.163766	132	0.109731		**Inlets & O**
35	**4/Sec**	11/03/99	0.8	0.2	0.6	192		1.86713		2333.91							**""**
36	**4/Sec**	12/03/99	0.8	0.2	0.6	146		1.403943		1754.93							**""**
37	**4/Sec**	19/03/99	0.8	0.2	0.6	145		1.393874		1742.34							**Inlet block**
39	**4/Sec**	29/03/99	0.8	0.2	0.6	145	152	1.393874	1.464359	1742.34	*1786.395*						**Inlet casc**
40	**4/Sec**	30/03/99	0.8	0.2	0.6	145	147	1.393874	1.414012	1742.34	*1754.929*						**""**
41	**4/Sec**	30/03/99	0.8	0.2	0.6	144	147	1.383804	1.414012	1729.76	*1748.635*						**Inlets & O**
42	**4/Sec**	30/03/99	0.8	0.2	0.6	190	193	1.846992	1.877199	2308.74	*2327.619*						**""**
43	**4/Sec**	31/03/99	0.8	0.2	0.6	70	80	0.650897	0.747289	813.621	*873.8662*						**""**
44	**4/Sec**	01/04/99	0.8	0.2	0.6	145		1.393874		1742.34							**Inlet block**
45	**4/Sec**	01/04/99	0.8	0.2	0.6	72		0.670107		837.634							**""**
46	**4/Sec**	01/04/99	0.8	0.4	0.4	130		1.242025		1552.53							**""**

CASE STUDY 4

Site 4 Treated Water Reservoir
Bacteriological Compliance and Cryptosporidiosis Incident

1. Background

Site 4 WTW receives water from a spring source. The untreated spring water is microfiltered, pH corrected and then disinfected with chlorine. The compliance point for the water treatment works is after the Site 4 treated water reservoir, which provides the disinfection contact time. This reservoir also receives water directly from an aqueduct (HA).

Hence the receiving zone is supplied by a blend of spring and aqueduct water. The ratio of the two flows is dependant upon demand and the availability of the spring source water.

Bacteriological Compliance

Site 4 WTW has a history of bacteriological non-compliance. In the past any coliform positive results were not considered to be directly attributable to either source water. It was considered more feasible that they could be caused by minor ingress, poor hydraulics / dead areas in the tank, the nominal retention time in the tank being excessive at approximately seven days. Lithium tracer tests conducted over a range of operational conditions during late 1998 were inconclusive due to poor recovery of the lithium trace.

Cryptosporidiosis Incident

An outbreak of cryptosporidiosis occurred in the supplied area in March 2000. The earliest onset of illness was reported on the 4th March, with the peak of the incident on the 10th March. As no incidents had been reported in distribution zones supplied with aqueduct water only it was easy to deduce that the spring water was the source of contamination.

The first outbreak control meeting was held on the 16th March and a 1627 litre sample was initiated at a pumping station, just downstream of the outlet from the reservoir. Analysis of the grab sample revealed 123 oocysts, hence a concentration of 76 per 1000 litres. The reservoir was bypassed from the 17th March and a boil water notice issued.

Prior to the incident the spring source was considered to be at significant risk for Cryptosporidium contamination using the DWI Risk Assessment Protocol. Looking at the rainfall data in the catchment area for that period, it was initially proposed that oocysts may have been washed off the catchment in the most recent period of heavy rainfall, occurring on the 2nd March.

If this was the primary contamination event, it would indicate:

- Significant short circuiting through the reservoir (nominal retention time 7 days)
- Individuals exposed to very high numbers of oocysts, with an unusually short incubation period (< 2 days)

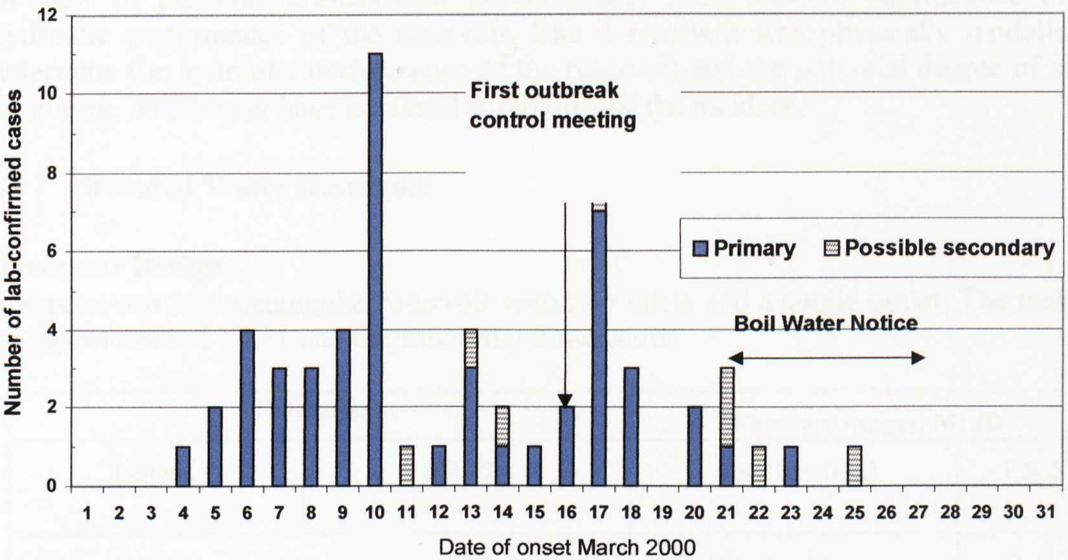


Figure 1: Number of lab confirmed cases of Cryptosporidiosis

In view of the large nominal retention time of the reservoir (>7 days) and the rapid onset, this was initially considered unlikely and the earlier heavy rainfall incident on the 27[th] of February was also implicated. See Figure 2:

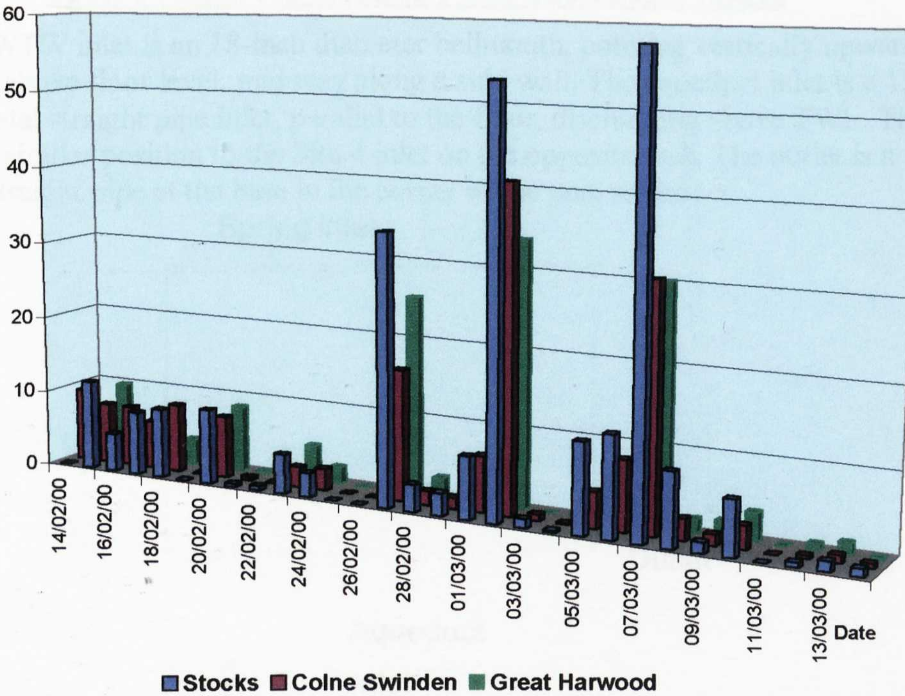


Figure 2: Rainfall (mm) in catchments supplying spring WTW

In view of previous unsuccessful lithium tracer trials and the significance of the hydraulic performance of the reservoir. Site 4 reservoir was physically modelled to determine the hydraulic performance of the reservoir and the potential degree of short-circuiting, which may have occurred at the time of the incident.

2. Treated Water Reservoir

Reservoir Design

The reservoir is a rectangular reservoir with two inlets and a single outlet. The tank has an aspect ratio of 1.2 :1 and the following dimensions.

Dimensions		**Flowrate ranges: ML/D**	
Length,	109.25m	Aqueduct (HA)	1.5- 5
Width:	90m	Site 4 Spring	2- 6
Operational Depth	3.5-5.4m	Outlet Flowrate	5- 10
Calculated Volume	53.1ML	Operational Depth	3-5 m

Table 1 : Reservoir Geometry and Operational ranges

The Site 4 WTW inlet is an 18-inch diameter bellmouth, pointing vertically upwards, located just above floor level, mid way along a side wall. The aqueduct inlet is a 12-inch horizontal straight pipe inlet, parallel to the floor, discharging above TWL. This is located in a similar position to the Site 4 inlet on the opposite wall. The outlet is a 12 horizontal straight pipe at the base in the corner of the tank as shown.

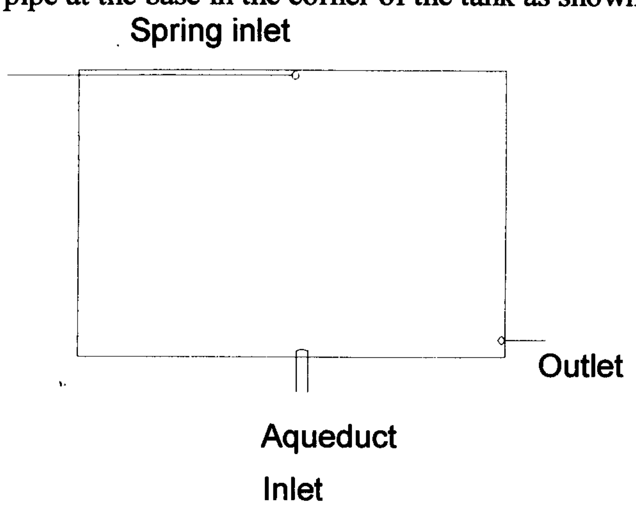


Figure 3. Schematic of Site 4 Reservoir

Reservoir Operation

The ratio of the aqueduct and springs water vary considerable during normal operation. In the past, after a period of heavy rainfall, Operations would often take advantage of the increase in availability of the spring source .

The generic modelling studies have shown that in cases where a reservoir has multiple inlets the flow pattern in the tank can change dramatically depending upon the nature, position and flowrate ratios of the inlets concerned. In addition as the level and flows in and out of the reservoir are varied the nominal retention time will vary accordingly.

The flowrate ratios and nominal retention times for the Site 4 Reservoir can vary considerably, and did so prior to and during the incident, see Figure 4. It is important to stress that this would be a normal response to supply and demand constraints..

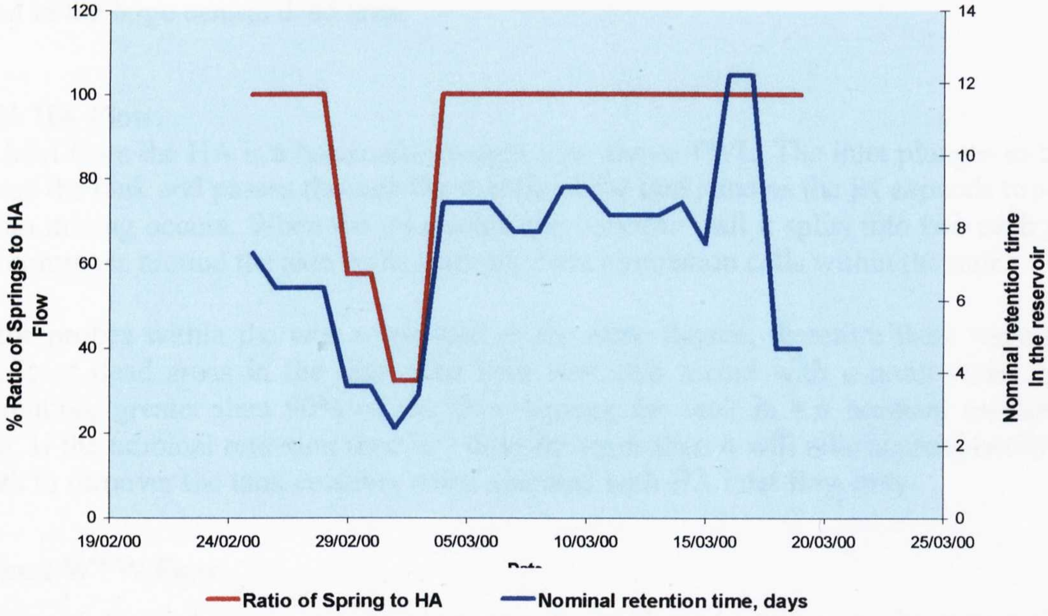


Figure 4. Inlet flowrate ratios and nominal retention times.

3. Reservoir Modelling

A physical model of Site 4 was constructed with a geometric scaling ratio of 32:1. As the ratio of the two respective inlet flows can vary, the baseline performance of the tank was evaluated over a range of operational, but steady state conditions.

A series of transient tests were then conducted to mirror the operation of the reservoir in the time leading up to and covering the incident until the boil water notice was issued.

3.1 Modelling Results

100% Site 4 WTW Flow.
The inlet from the WTW is an upturned bellmouth near base level of the tank. The incoming flow rises as a vertical jet and begins to spread out across the surface of the tank. The flow then effectively splits into two jets, which are channelled by the side walls. The dominant jet travels around the periphery of the tank reaching the outlet first. The general result is a circulation around the outside of the tank with a large central dead area. The flow visualisation dye tests are shown in Figure 5.

Analysis of the residence time distribution curve showed that under these conditions there is little short-circuiting. The inlet jet is well dispersed before the leading edge of the flow reaches the outlet. However there was very poor recovery of the salt trace and in some instances as much as 40% of the salt pulse was not recovered. This was being stored in the large central dead area.

100% HA Flow.
The inlet from the HA is a horizontal straight pipe above TWL. The inlet plunges to the base of the tank and passes through the middle of the tank, and as the jet expands top to bottom mixing occurs. When the jet reaches the opposite wall it splits into two each jet then continues around the side walls, forming twin circulation cells within the tank.

All the probes within the tank responded to the same degree, therefore there were no significant dead areas in the tank. The tank was well mixed with a good water age distribution, greater than 90% of the flow leaving the tank in 4.6 nominal retention times. If the nominal retention time is 7 days however then it will take approximately 1 month to turnover the tank contents when operated with HA inlet flow only.

HA and WTW Flow

A series of dye and steady state tracer tests were conducted varying the flowrate ratios of the two respective inlets. The results showed that the HA inlet has a dominant effect on the flow pattern in the tank. This is because the jet has much greater directional momentum that the WTW inlet.

Figure 6. shows dye tests which were conducted with 65% WTW : 35% HA flow. The red dye is from the WTW inlet and the blue from the HA. The HA water jets through the centre of the tank as anticipated. The HA flow doesn't reach the end of the tank as previously but splits earlier into two jets, one of which short circuits to the outlet. The HA flow is the first to reach the outlet. The dominant flow path for the WTW inlet is significantly affected. When the HA is introduced the WTW again forms two jets.

However one jet takes the shortest route to the outlet, reaching the outlet after the leading edge of the HA flow.

Hence operating with both HA and Site 4 WTW water leads to a greater degree of short-circuiting for both inlet flows. The dilution effect is however still greater than that achieved by other inlet / outlet designs. The modelling results indicate that the peak concentration at the outlet will only be approximately 0.8% of the inlet pulse. This will change as a result of changes in operation but not significantly. It should be noted that what is the most quiescent area of the tank when the 100% WTW works flow is used, becomes the most turbulent part of the tank when HA only flow is used.

Comparison with full scale lithium results

Four full scale Lithium tracer tests were conducted in October to November 1998. Each test was conducted over a week in line with the large nominal retention time. Each test resulted in a negligible, straight-line trace at the laboratory minimum limit of detection. After each unsuccessful trial the inlet trace concentration was doubled.

The maximum inlet pulse concentration used was 329 mg/l as lithium. Under these conditions the physical modelling predicted peak concentration at the outlet would be 2.6 mg/l lithium. The limit of reliable detection by the analytical laboratory was 5 mg/l. Hence it is not surprising that no effective trace was seen with the lithium results. At least four times this initial concentration would have been required to produce any discernible trace.

3.2 Summary Baseline Tank Performance

Operation of the tank with HA inlet flow only leads to the best hydraulic performance in terms of elimination of dead areas and shortest water age distribution. The minimum continuous inflow to achieve turbulent mixing with an inlet of this diameter is 0.09ML/D.

Operation of the tank with WTW flow only leads to a peripheral circulation, with the dominant jet taking the longest route to the outlet. Good dispersion of the inlet flow is achieved, there is negligible short circuiting. However the is a very large central dead area. A minimum continuous flow of 0.13 ML/D is recommended to achieve any mixing at all.

Operation of the tank with both HA and WTW flow leads to the poorest hydraulic performance. It results in short circuiting of both inlet flows to the outlet, poor mixing and significant dead areas.

If the tank is operated with WTW flow only for a significant period, dead water located in the centre and any sediment which may have accumulated will be flushed directly to the outlet when the HA flow is introduced. This probably presents the greatest risk to general water quality in supply.

During normal operation the flow pattern in the tank will go through a series of transients as the flow is changed between these three main conditions.

4. Cryptosporidiosis incident

In the light of the variable performance of the reservoir, a number of detailed transient state test were conducted where the flows and levels were altered in line with the reservoir operation prior to and during the time of the incident.

Test series 1

It was assumed that the first "injection" of oocysts came into the reservoir on the 27th February after the first associated heavy rainfall incident. This was modelled by injection of a salt pulse into the reservoir model via the WTW inlet. Monitoring of the salt at the outlet of the tank gives corresponding concentration and times for the salt / oocysts leaving the reservoir. Using the actual concentrations taken in the grab sample on the 17th March one can estimate the peak concentrations an individual may have been exposed to and when this was likely to have occurred.

The results from these initial tests indicated that due to the mode of operation of the reservoir an its low nominal retention time (2 days) during some of this period. A large spike of oocysts entering the reservoir from the WTW inlet on the 27th February would have been effectively washed out by the time the grab sample was taken on the 17th March.

Test Series 2

It was then proposed that there were potentially two contamination events, after each significant rainfall event on the 27th February and the 2nd March respectively. This was modelled, by injection of two discrete salt pulses into the model WTW inlet at the appropriately scaled time in the modelling run.

The test gave 85% salt recovery; this was probably attributable to the drop in the background conductivity going into the model. Applying an exponential decay curve to the trace after the point where the background had begun to decay gives a smoother decay curve. The resulting residence time distribution curve is shown in Figure 7. There are three significant peaks:

The first is the expected peak as a result of the tank operating initially with just WTW flow, this would have occurred on the 29th February. The second comes on the 1st March as a result of the introduction of HA flow. The final peak occurs on the 2nd to the 3rd March after the second salt pulse (rainfall incident) is introduced. Based upon the concentration found in the sample of the 17th March the most probable concentration that the receiving population would have been exposed to was 40 times greater, approximately 30 oocysts per 10 litres.

These values are based on tests where the pulse was introduced instantaneously; in practice it is likely that the contamination of the reservoir took place over several hours/ days after each major rainfall event and lower levels could be coming in on a daily basis. These numbers should not be considered exact, but are a good indication of level of exposure over the period in question.

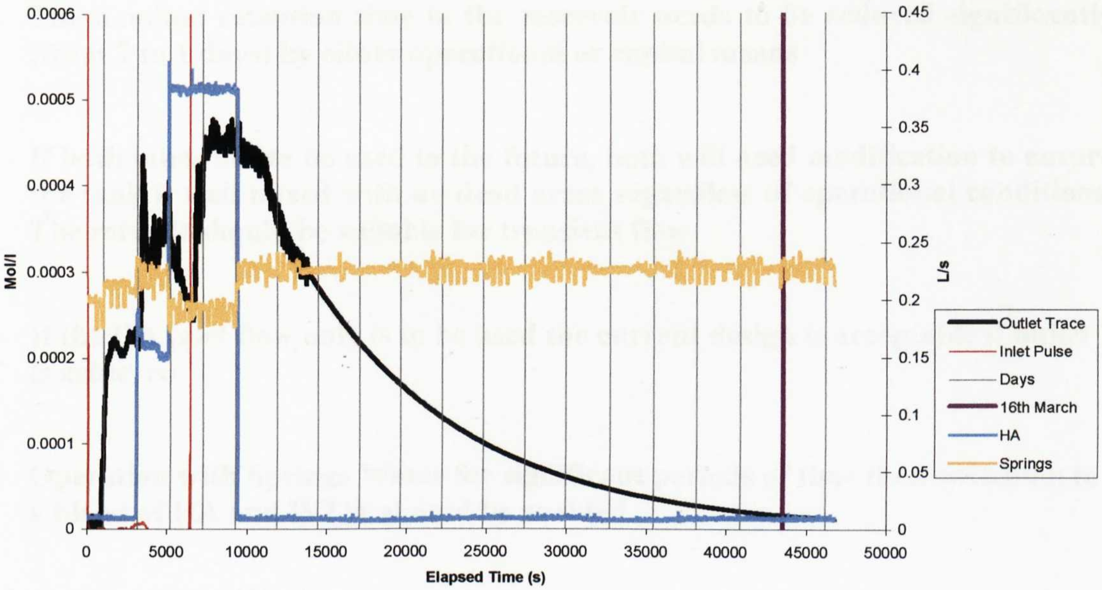


Figure 7. Transient tests –incident modelling

The reservoir is hydraulically poor, with at times excessive retention time. In this instance the large degree of dilution of the inlet trace due predominantly to the WTW inlet design and size of the tank resulted in relatively low maximum concentrations. This probably afforded the public some degree of protection. If both inlets had been of a different design the maximum concentrations would have been much higher and it is possible that increased numbers of healthy individuals would have been infected.

5. Conclusions & Recommendations

5.1 General Water Quality

Site 4 reservoir is hydraulically most efficient when the aqueduct inlet only is used. Under these conditions mixing is good and >90% of the water will be exchanged in 4.6 nominal retention times.

As the nominal retention time can be of the order of 7 days then at best one would expect 90% water exchange in the tank to take in excess of a month.

Under any other flow conditions the performance of the reservoir is extremely poor. Large dead areas exist, mixing is poor.

If the WTW inlet only is used, a large central dead area is formed. When the HA flow is introduced the water stored in this area short-circuits to the outlet.

- **The nominal retention time in the reservoir needs to be reduced significantly (from 7 to 1 days) by either operational or capital means**

- **If both inlets are to be used in the future, both will need modification to ensure the tank is well mixed with no dead areas regardless of operational conditions. The retrofit should be suitable for transient flow.**

- **If the HA inlet flow only is to be used the current design is acceptable if bullet 1 is achieved.**

- **Operation with Springs Water for significant periods of time then switching to a blend of HA and WTW should be avoided.**

5.2 Cryptosporidiosis

The catchment supplying the spring WTW was at risk of Cryptosporidium contamination and the current treatment processes at Site 4 WTW do not provide a barrier.

Individuals were probably exposed to levels of 3 oocysts per litre during the peak of the contamination incident. The low peak concentrations are a function of the WTW inlet design.

- **The Springs source should not be utilised until either an adequate cryptosporidium barrier treatment is in place or contamination of the underground source by surface water is prevented.**

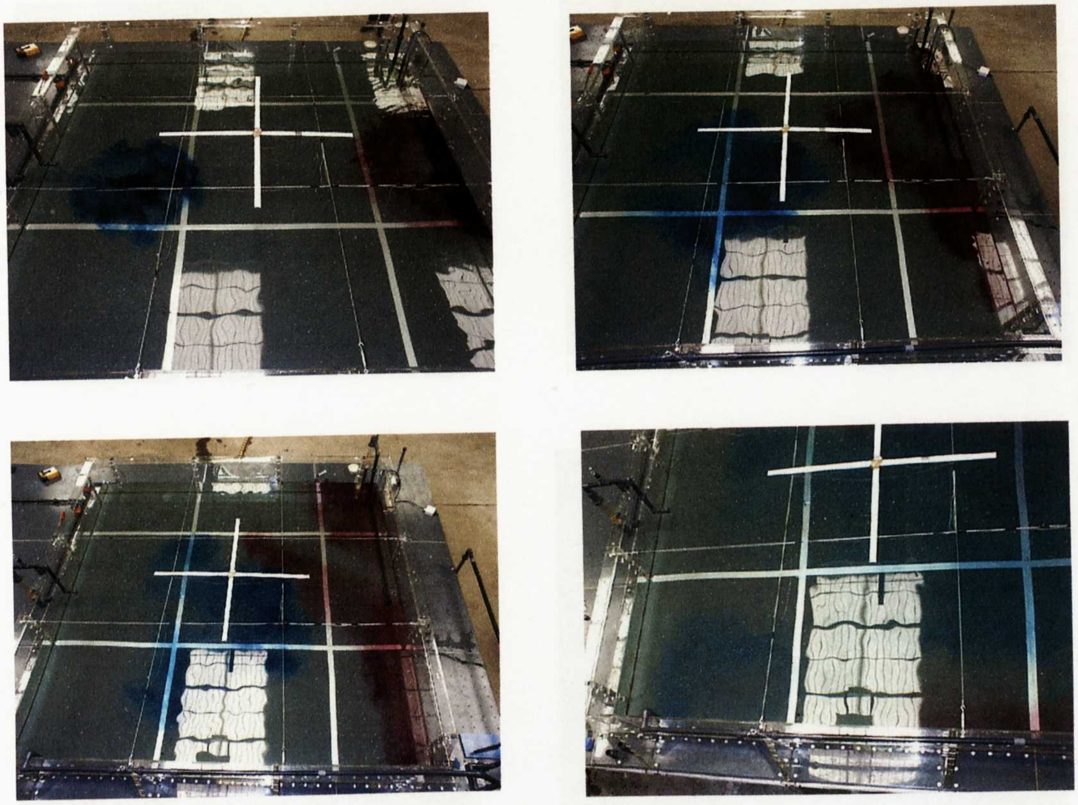


Figure 5.: 100% Site 4 WTW flow

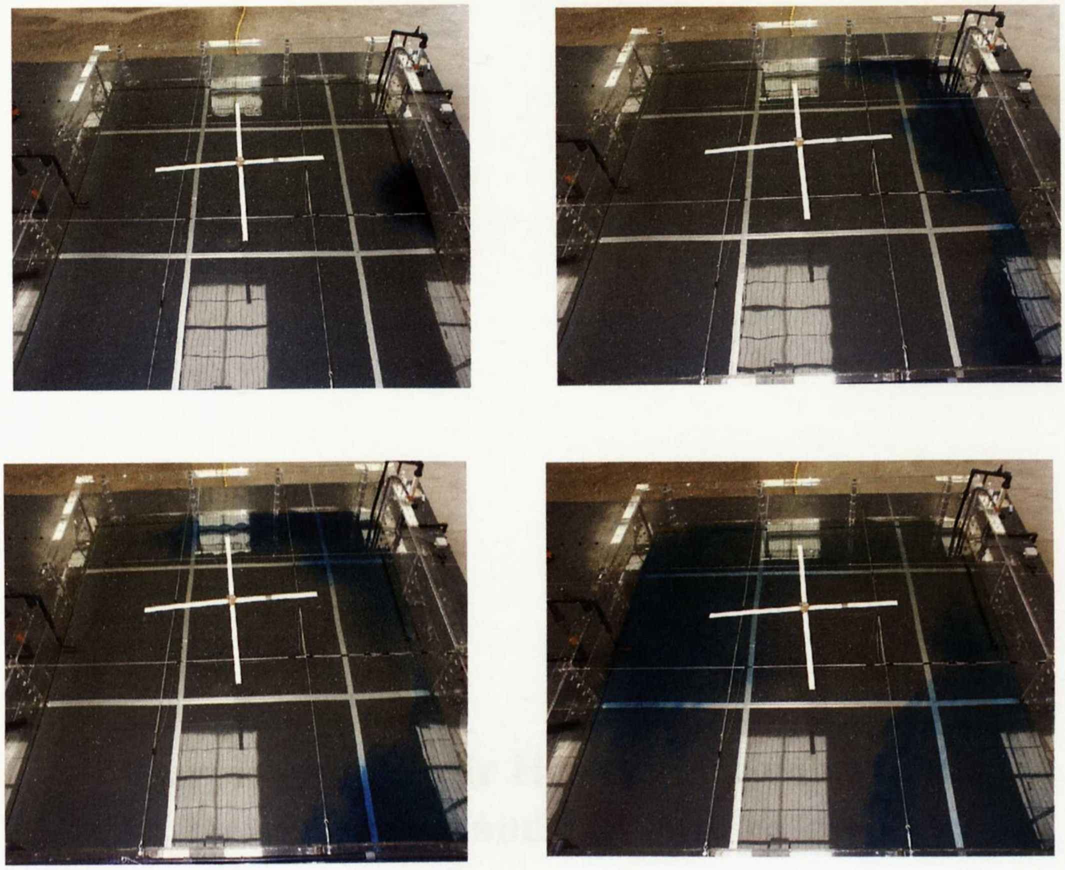


Figure 6:

65% WTW 35% HA Flow

WTW inlet -red dye:

HA inlet -blue dye

Service Reservoir Hydraulic Evaluation Design Guide and Retrofit Manual.

Appendix D

INTRODUCTION

This manual gives a step by step guide for the assessment of the hydraulic performance of service reservoirs. It is based upon the results of an extensive programme of physical modelling with over 300 individual modelling tests. Several performance parameters have been identified. In using this manual, one will have to identify which generic group the individual asset to be assessed falls into, and use the performance parameters given.

One of the key performance parameters that has been used in this document is water age. Water age has been used as a surrogate for water quality. Water is assumed to have a shelf life and the key to hydraulic optimisation is to ensure adequate turnover of the stored water by design, without the requirement to 'work' the reservoir.

The guide is intended to be generic in nature. An initial review of 150 of North West Water's 400 service reservoirs set the scope of the modelling programme. The generic groups of reservoirs were defined as result of the performance characteristics found during the modelling.

Therefore if the guide does not cover the exact operation or design of an individual service reservoir, using the most similar asset type and mode of operation will give a good indication of expected performance.

It is important to note that the recommendations given in this document are for general guidance. The values given for performance indices should not be considered as precise but indications of expected performance.

These guidelines should be used to appraise designs of all existing service reservoirs and designs for new assets. This guidance manual is a primary reference source to which reference is made in the Service Reservoir Asset Standard, August 2000.

Definition of a Service Reservoir

It is important to ensure that the guide is used in the correct context.

Any storage tank in distribution whose primary function is **not disinfection** should be classified as a service reservoir. This should include all tanks for the purposes of balancing flow, pressure or maintain security of supply.

Tanks whose primary function is to provide adequate contact time for disinfection should be assessed and optimised using the design guidelines recommended in the WTW Asset Standard, and Report on Contact Tanks.

The results may be applied generally to other similar mixing applications. However they must not be used for non-Newtonian fluids i.e. sludge.

Appendix D

OVERVIEW OF HYDRAULIC EVALUATION DESIGN GUIDE AND RETROFIT MANUAL

The hydraulic review of a service reservoir is part of the ongoing activities aimed at improving water quality in distribution. Each assessment should therefore begin with an asset audit. It is important to ensure that all of the information is correct and up to date. The audit should cover the design, operation, instrumentation and all associated water quality issues. A suitable guidance audit document is given in Appendix 1.

The audit when complete should highlight areas of concern or poor performance. It will also provide the necessary information for the hydraulic assessment to be carried out. The results of the hydraulic assessment should subsequently show areas of poor performance and give guidance on the potential for improvement by appropriate retrofits or operational changes.

Hydraulic Performance

The hydraulic performance of a service reservoir is predominantly determined by:

- the tank shape
- the tank aspect ratio,
- the size, position and nature of the inlet and outlet pipework
- the flowrate and frequency of flow into and out of the reservoir

This is the minimum amount of information, which is required to proceed with the hydraulic appraisal. Internal structures such as benching, baffling and structural supports can also influence the performance so their positions and relative size should also be known.

PERFORMANCE MEASURES

The reservoir performance can be characterised by a number of parameters:

❖ The water age distribution

This is the spread of age of water that has passed through the reservoir. The percentage of water passing through in a given time (t).

The nominal retention time T, is a very important parameter, it is the anticipated storage time and is given by the volume in use divided by the flowrate though the reservoir.

In most cases a significant percentage of the water exits before the nominal retention time. A sharp early peak is indicative of short-circuiting.

A percentage of the water takes a much greater time to leave the tank – long exponential tail of the curve. These long tails in the curve are symptomatic of dead areas in the tank.

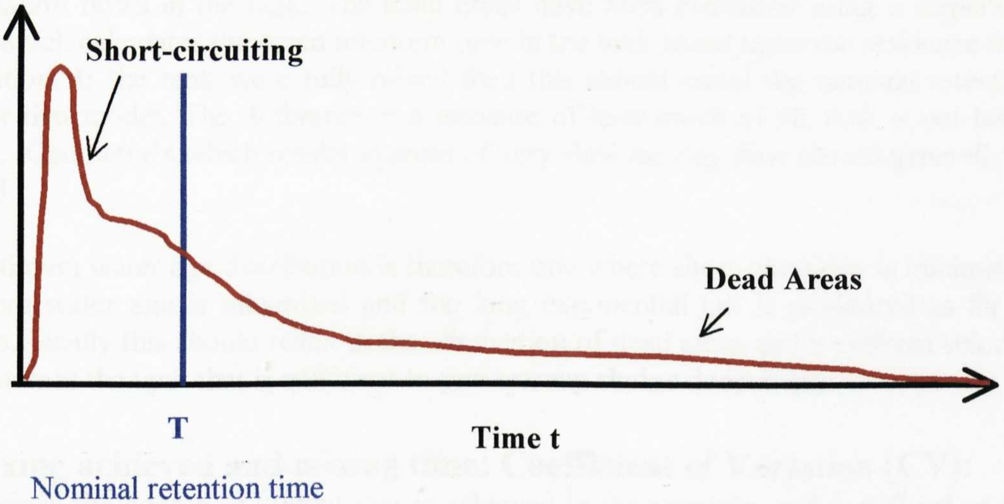


Figure 1. Water Age Distribution

The water age distribution is like the hydraulic fingerprint of the tank. Tanks that are generically similar will have a similar water age distribution. Therefore one can analyse the water age distribution and predict levels of performance in similar assets when operated within similar boundaries.

❖ Dead Areas

These are areas of the tank where water is very slow moving and any particles in suspension in the water are more likely to settle out as sludge on the base of the tank.

There is much poorer water exchange between these areas than the rest of the tank. Residual disinfectant levels may be very low, THM levels may be high due to high water age, oxygen levels may be low and there may be the potential for coliform recovery and multiplication.

Consequently it is easy to appreciate why these "pockets" of water can contribute to significant taste / odour, bacteriological non-compliance, THM failures and dirty water incidents if released, in a plug, with their associated sludge deposits into the distribution system.

Generally what is received at the outlet of a reservoir is a blend of water with different age distribution and quality characteristics, which results in the final water quality as sampled.

However in certain operational conditions such as peak demands or bursts, a significant percentage of older water can be pulled out as a plug and this can result in associated quality issues in the network.

Estimation of the quantity of dead volume in the tank can be difficult. Various models have been used in the past. However they are prone to large errors when there are strong recirculation flows in the tank. The dead areas have been estimated using a dispersion model which calculates the mean retention time in the tank based upon the residence time distribution. If the tank were fully mixed then this should equal the nominal retention time for that model. The difference is a measure of how much of the tank is not being utilised. Geometry's which results in areas of very slow moving flow should generally be avoided.

The optimum water age distribution is therefore one where short-circuiting is minimised, maximum water age is minimised and the long exponential tail is minimised as far as possible. Ideally this should result in the elimination of dead areas and a uniform velocity profile across the tank that is sufficient to prevent any sludge deposition.

❖ Mixing achieved and mixing time: Coefficient of Variation (CV):

This defines the degree of mixing that is achieved in the reservoir and is defined as the standard deviation divided by the mean concentration. A CV of 0.05 indicates that the contents of the reservoir are 95% percent mixed. The time to achieve mixing will also be important. If mixing is achieved rapidly then the tank may be able to cope better with intermittent flow. Chlorine residual will be more rapidly buffered by incoming flow with a typically higher chlorine concentration.

It is important that the contents are mixed because changes in quality in the incoming flow will be buffered out in the tank and not passed directly into distribution. This will become increasingly important with the increased flexibility needed when moving water around the distribution system to facilitate future common carriage.

Customers, especially industrial customers are very sensitive to changes in quality.

❖ Dilution Factor:

This is a measure of the initial dispersion in the tank. For example, this may be assessed by considering a spike of contaminant entering the reservoir and its likely maximum concentration on exiting the reservoir.

This may be a useful factor to know, if reservoirs are to be used to blend waters with different characteristics. Or if there were ever to be a short-term infringement of a quality parameter at a WTW, one may have confidence that this would not result in a similar infringement in distribution. In addition it is important to know the duration over which an infringement may continue before it becomes a problem in the distribution system.

❖ Flow pattern stability

If the dominant flow pattern in a service reservoir is unstable, it may be likely to go through transient flow patterns depending upon operational factors such as inlet & outlet flow and level variations, etc.

In these circumstances areas of the tank which were previously prone to deposition can become mixed areas, as a function of operational change. This can result in volumes of "older water" with associated settled deposits being drawn into distribution i.e.: Dirty water incident. Hence stability of the flow pattern is an important factor.

In addition disinfectant residual losses are greater from a plug flow tank rather than a completely mixed tank. This is due to the buffering effect of the incoming flow with a typically higher disinfectant residual. This is shown by presented by Grayman (1999) on behalf of the American Water Works Association,

The optimal design is one which ensures that the service reservoir

- **Is completely mixed**
- **has no dead areas**
- **reduces maximum water age as a function of the design**
- **has limited short circuiting**
- **hydraulic performance is stable with respect to operational changes**

To achieve the above in a refurbished or new reservoir the current and future operational regime of the reservoir needs to be established first.

Whether a reservoir is likely to be operated with some degree of continuous flow or intermittent flow will determine the most appropriate design, position and type of inlet and outlet arrangement.

Appendix D

USING THE GUIDE

The guide may be used to:

(a) Evaluate the performance of an existing service reservoir : **Flowchart 1**
(b) Or to design a new service reservoir. **Flowchart 2**

Select either flowchart 1 or 2 to take you through the guide. One should be able to flip the specific flowchart open and follow the sequence recommended to either evaluate / retrofit an existing reservoir or design a new service reservoir.

At each stage the guide will list information which is required to proceed to the next stage of the assessment. It will indicate how to use the information presented to either evaluate / retrofit an existing reservoir or design a new reservoir.

The guide is structured using simple pictures and performance measures. The calculations that have been included have been simplified and are essential to the process.

The Key Performance Indicators that have been predominantly used to assess design are water age and the percentage dead area in the tank. Other parameters such as the dilution factor and percentage short-circuiting may be of particular interest for individual sites.

A design should never be considered acceptable if the hydraulic performance is not stable over the full range of anticipated current and future operational regimes. This is detailed in the guide.

Tanks are assessed in terms of general shape, aspect ratio, inlet / outlet type, position and operation. The recommendations in this design guide have been based upon physical scaled modelling using:

- **Steady state tests**: Where the flows in and out of the tank are equivalent and therefore the level remains constant.
- **Transient Tests:** Where the flow in and out is intermittent and level varies, fill and draw type operation

The implications in terms of performance and stored water age, of operating different types of tanks in fill / draw modes and steady state mode are also defined.

For simplicity the results presented are those determined under **steady state conditions**. The water age characteristics are given in terms of multiples of T, the nominal retention time. The implications of operating the tank with intermittent flow are given.

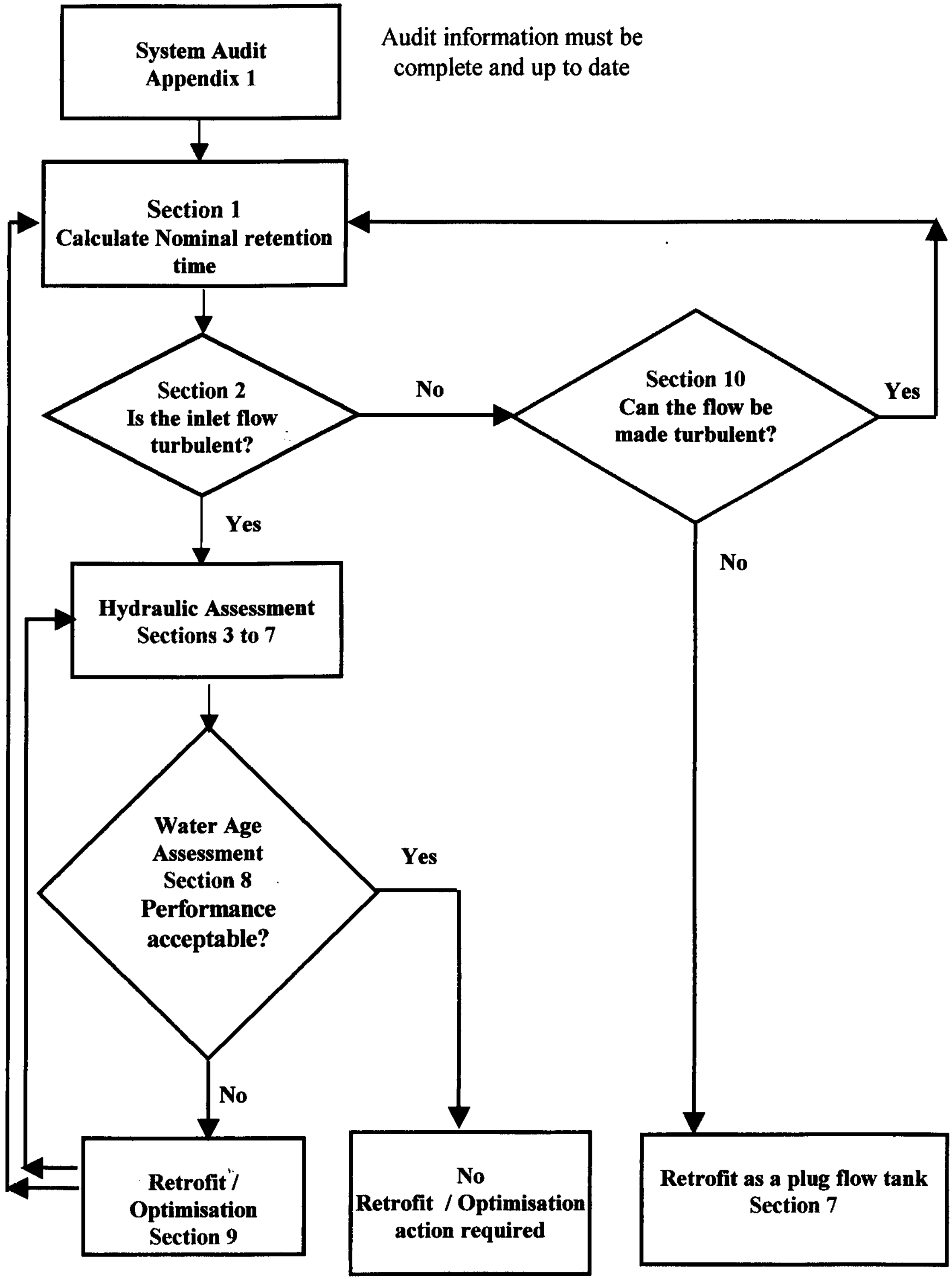
In each section the assets are arranged in order of performance, hence for a given geometry the inlet and outlet defined in example (a) perform better than the inlet and outlet arrangement described in (b).

However one must note what operational boundaries apply to that geometry: ie To be operated with continuous inlet and outlet flow.

Appendix D

Flowchart 1

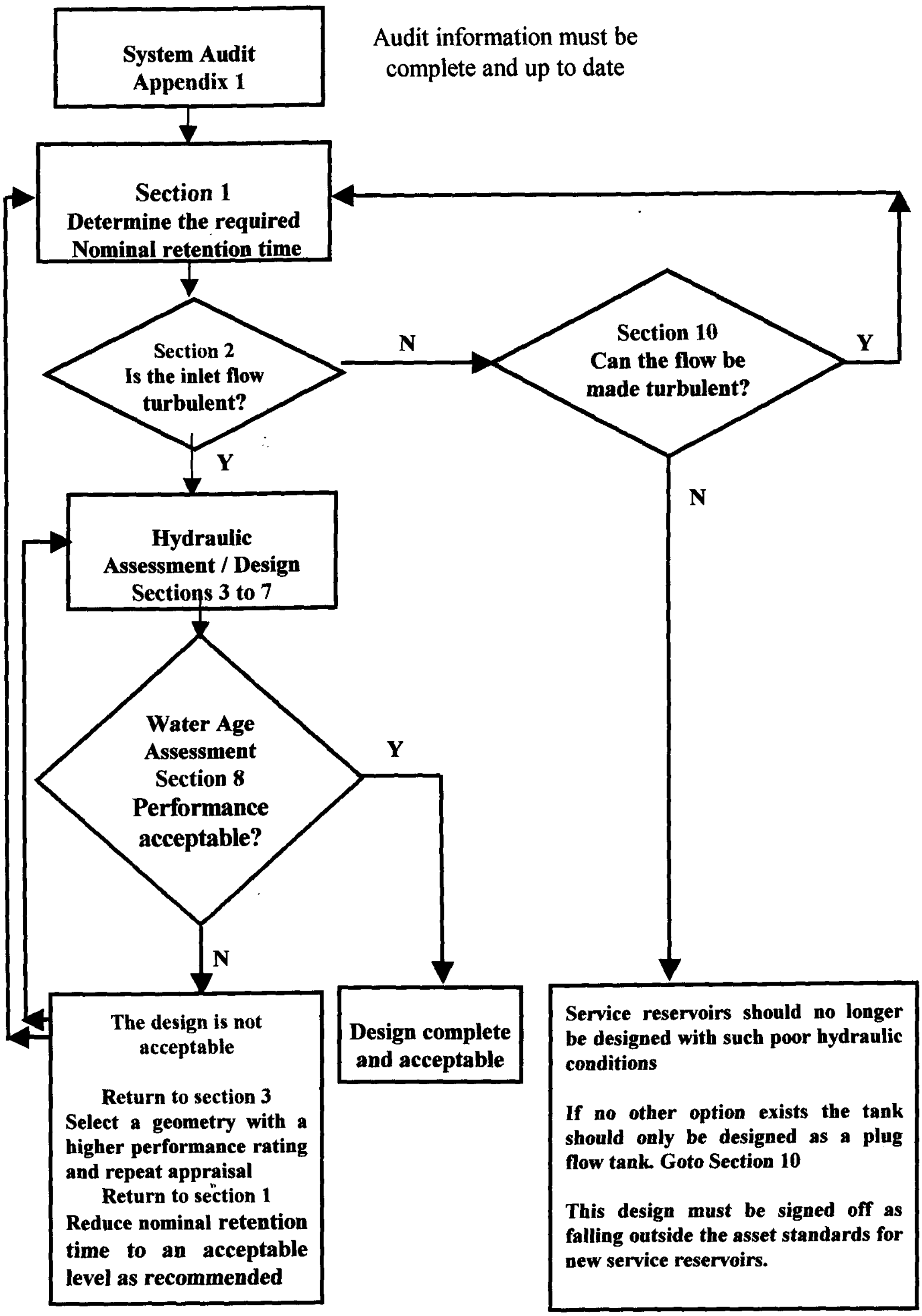
Evaluating / retrofitting an existing service reservoir



Appendix D

Flowchart 2

Assessment and validation of a new service reservoir design



SECTION 1.
DETERMINE / CALCULATE THE NOMINAL RETENTION TIME

Information required

- The operational volume of the reservoir (m3)
- The average daily flowrate (m3/d)

> **Evaluating existing designs**
> For an existing reservoir the information should be available following the audit
> **New Design**
> For a new tank the information on required storage volume will have to be defined by risk assessment, the current and future operational demands of the distribution network, in line with the Service Reservoir Asset Standards, August 2000.
> An indication of the flow that will be passed through the tank should be available.

1.1 THE NOMINAL RETENTION TIME (T)

The nominal retention time expressed in days is given by:

$$\frac{V}{Q}$$

Where:
V= the operational volume of the reservoir (m3)
Q= the average daily flowrate into the tank (m3/d)

This value is important and will be used again after the main appraisal has been concluded.

The nominal retention time should ideally be of the order of 1 day and no greater. Generally 24 hours storage time is considered sufficient in terms of security of supply. For existing reservoirs a reduction in demand or leakage may have resulted in an increase in nominal retention time. There may be site specific reasons why this is greater than 1 day.

1.11 Guidelines

i) Retrofits

If the nominal retention time of an existing tank is greater than 1 day then operational optimisation should be considered first. There may be security of supply / risk reasons why this is the case. Each site should be considered individually.

ii) New Tank Design

The designed nominal retention time should be 1 day and certainly not in excess of 2 days.

The nominal retention time is a measure of the storage volume but it does not reflect the true age of the water stored in the tank. Therefore there are likely to be penalties in terms of increased chlorine demand and continued quality compliance issues if service reservoirs continue to be built with excessive storage.

SECTION 2
WILL MIXING OCCUR?

Information required / to be determined

- The actual inlet flowrate
- The frequency and duration of the inlet flow
  I.e. continuous, infrequent for 2 hours every day
- The diameter of the inlet pipework

Evaluating existing designs
For an existing reservoir the information should be available following the audit
New Design
For a new tank site specific parameters will normally define the inlet flow available. However the diameter of the inlet pipework and the frequency and duration of flow in and out of the tank should be optimised with due regard to the guidelines given below.

2.1 HOW FREQUENT IS THE INFLOW?

- Add up the number of hours in a day that flow enters the tank
- Divide the number of hours by 24
- Express the number as a percentage

The best mixing is achieved and the most homogeneous result in terms of water quality is achievable when the flow into the tank is continuous.

Intermittent inlet and outlet flow results in step changes in quality of water leaving the tank.

The inlet flow must be on for sufficient time for mixing of the tank contents to take place. The time that is required is dependent upon the tank configuration.

2.11 Guidelines

i) Retrofits
With an existing service reservoir there may not be sufficient scope to easily improve the frequency of flow into and out of the tank. However if the percentage inflow is <25% then control of water quality leaving the tank will be compromised.

ii) New Tank Design
With a new service reservoir, there may be some limitations on the way in which the site is supplied. However the ideal scenario is to operate with continuous inlet and outlet flow.

2.2 WILL THE INLET FLOW PROMOTE MIXING

The inlet flow, during periods when it is operational must be turbulent to achieve any mixing within the tank. If the inlet flow is not turbulent negligible mixing will be achieved, regardless of the inlet type. This must be determined for each inlet in a multiple inlet tank.

To determine if the inlet flow is turbulent we need to calculate the Reynolds number (Re). For the inlet flow to be turbulent the Reynolds number must be greater than 3000.

Where

$$\mathrm{Re} = \frac{4Q}{\pi D \upsilon}$$

Q = The inlet flowrate (m3s-1)
D = The inlet diameter (m)
υ = The kinematic viscosity of water m2s-1

2.21 Guidelines

i) Retrofits
Reynolds numbers into service reservoirs are typically of the order of 100,000. A Reynolds number of 10,000 is considered very low. Hence to have Re as low as 3,000 would be considered extreme.

ii) New Tank Design
For a new service reservoir the aim should be to achieve inlet Reynolds numbers of the order of 100,000. Inlet Reynolds numbers of less than 10,000 should be considered unacceptable.

If Re is <3000
The flow is not turbulent and extremely poor mixing will occur
Proceed to section .10.

If Re is >>3000, the inlet flow is turbulent
Process to section 3.

NOTE: A Reynolds number <10,000 is considered very low. In these instances an assessment should be carried out to ensure that the flow would be turbulent under all operational conditions.

SECTION 3:
GENERIC TYPE OF TANK

Information you will need to know to proceed:

- ❑ The shape of the tank

Evaluating existing designs
For an existing reservoir the information should be available following the audit
New Design
For a new tank the shape of the tank may be determined by site restrictions. Or there may be limitations in terms of capital costs. If no limitations occur select the tank type with the highest performance rating which meets the individual site requirements.

If the tank is rectangular, including square tanks: **go to section 4**

If the tank is circular: **go to section 5.**

If the tank does not fall into either category: **go to section 6.**

If the tank is already baffled **go to section 7.**

3.1 USING SECTIONS 4 AND 5.

In sections 4 and 5 that follow, tanks are characterised in terms of aspect ratio. Schematics and brief descriptions are used to describe common inlet and outlet arrangements. The flow patterns and hydraulic performance parameters for these configurations are shown and discussed, recommendations for retrofits to improve performance are also given.

The configurations are listed in order of performance so that in each section (a) has a better performance than (b) etc.

In going through sections 4 or 5.

i) **Existing tank evaluation**

- Select the inlet / outlet arrangement and aspect ratio that best describes your individual tank / compartment.
- Read the performance assessment and the impact of changes in operation
- Go to the performance tables at the end of the section and note the performance parameters.
- Make a note of the suitable retrofit options recommended
- Proceed to Section 8. to complete the evaluation

ii) **New Design**

- Select the aspect ratio that best describes your individual tank / compartment requirements
- Start at example (a) and work through each example until you reach one that satisfies all site requirements.
- Read the performance assessment and the impact of changes in operation
- Go to the performance tables at the end of the section and note the performance parameters.
- Proceed to Section 8. to evaluate the performance of the design in terms of water age.

NOTE:
If a new design requires multiple inlet / outlets. Select the example which gives the best performance based upon a single inlet / outlet.

Design the multiple inlet / outlet system such that all of the inlet jets discharge from the multiple system in the same manner as the single system. Where inlets are above TWL they must be positioned in the same place.

Alternatively and preferably combine the inlets before entering the tank such that there is only a single inlet into the tank. Similarly take a single outlet from the tank.

SECTION 4
RECTANGULAR TANKS

Information you will need to know to proceed:

- ❑ Tank / compartment length
- ❑ Tank / compartment width
- ❑ Tank depth
- ❑ The number of inlets and outlets
- ❑ Each inlet type, size and position
- ❑ Each outlet type, size and position

Evaluating existing designs
For an existing reservoir the information should be available following the audit
New Design
For a new tank the aspect ratio of the tank may be determined by site restrictions. The number of inlet sources should be defined. There may be some requirement for either high or low level inlets. Whether twin compartments are required should also be known. With these basic requirements select the tank type with the highest performance rating which meets the individual site requirements. The flow split to the compartments should be designed with reference to Appendix 2.

4.1 Does the tank have twin compartments, a dividing wall?

For the purposes of evaluation at this stage it does not matter if the wall is mid or full height. Each compartment should be considered as a separate tank with individual inlet and outlet arrangements. The explanation for this will be made clear in the subsequent sections.

4.2 Is the flow split evenly to the twin compartments

If the whole reservoir is fed from a common source then the inlet pipework design **must** ensure that each reservoir compartment receives the correct proportion of the available incoming flow, based upon storage volume in use. Guidelines for appropriate design of inlet pipework and common poor design are given in **Appendix 2.**

4.3 Calculate the length to width (L/W) ratio for the tank / compartment.

This is important because the flow pattern in the tank, for the same operational conditions, and inlet / outlet arrangement will change as a function of the length / width ratio of the tank.

If L/W is	**1:1 to 1.4:1**	**go to section 4.4**
If L/W is	**>1.4:1 & <1.8**	**go to section 4.5**
If L/W is	**1.8:1 to 2.3:1**	**go to section 4.6**
If L/W is	**2.3:1 to 2.8:1**	**go to section 4.7**
If L/W is	**2.8:1 to 3.5:1**	**go to section 4.8**

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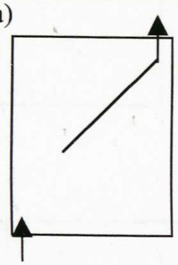
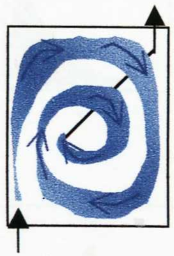
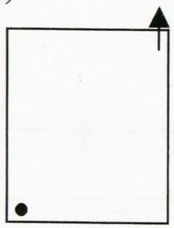
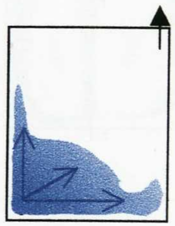
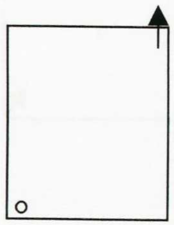
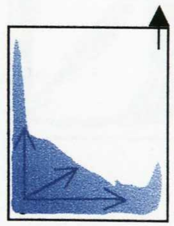
Section 4.4:Tanks / Compartments with Aspect ratios of 1:1 to 1.5:1

Schematic	Description	Flow Pattern and Tank Performance Bar Chart Water age distribution		Retrofit Options
(a) 	**Inlet** : Horizontal straight pipe inlet at base level parallel to side wall **Outlet**: Horizontal straight pipe, at base level, from centre of tank		Strong recirculation flow pattern, flow spirals into central outlet. Relies upon some level of continuous inlet and outlet flow to maintain performance ✓ No dead areas. ✓ Most rapid complete water exchange ✓ Good degree of mixing **If outlet flow not continuous reverts to example (L) and performance deteriorates. Percentage inlet flow should ideally be >50%**	No retrofit required **The tank should be operated with continuous flow. Do not use design where intermittent outlet flow occurs.** If this does not occur then at least oldest water will be taken out first
(b) 	**Inlet** : Downturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Flow spreads out radially from the inlet Highest velocities across the base of the tank Some short circuiting occurs along the walls Slowest moving flow sometimes in the centre of the tank ✓ Good mixing ✓ No significant dead areas ✓ Reasonable time for complete water exchange **Baseline performance does not deteriorate with intermittent flow.**	The best performance from a high level inlet, with this geometry. Option (a) above has better baseline performance **but only when operated with continuous flow.**
(c) 	**Inlet** : Upturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Flow spreads out radially from the inlet Highest velocities across the base of the tank Short circuiting occurs along the walls Can occasionally be small dead area in the centre of the tank ✓ Good mixing ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow.	Option (b) has improved performance

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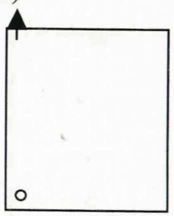
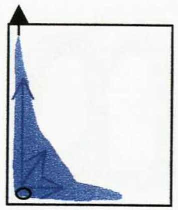
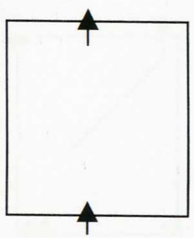
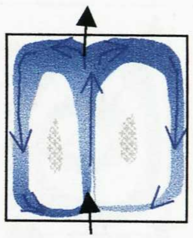
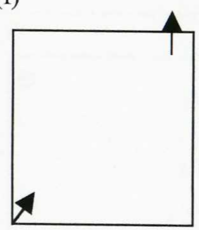
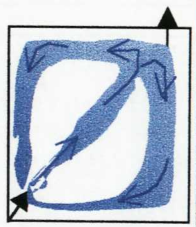
(d) 	**Inlet** : Upturned bellmouth above TWL **Outlet:** Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		Flow spreads out radially from the inlet Highest velocities across the base of the tank Greater short circuiting occurs along the walls than (c) Can occasionally be small dead area in the centre of the tank ✓ Good mixing ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow.	Retrofit option (b) has the best performance for high level inlets with this geometry Option (a) above has better baseline performance if low level inlets can be used, **but only when operated with continuous flow in and out.**
(e) 	**Inlet**: Submerged horizontal straight pipe at 90° to side wall, mid wall. **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		The inlet jet progresses through the middle of the tank and forms two circulation cells. Small quiescent areas may be found in the centre of each circulation. The size will depend upon the aspect ratio of the tank. The inlets should be parallel to the longest side to minimise dead areas. Mixing is rapid The degree of mixing is good Some short-circuiting occurs. Multiple inlets can be arranged in a similar manner.	Alternatively ensure that inlet flow is turbulent and inlet duration is sufficient to achieve complete mixing in the tank. If short circuiting must be eliminated, (a) may eb considered **only if continuous inlet and outlet flow are assured for all current and future operation.**
(f) 	**Inlet** : submerged horizontal straight pipe, pointing diagonally across tank **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally opposite		The inlet jet travels diagonally across the tank and splits into two recirculation cells as shown. With small quiescent areas in the centre of each cell. The modelling showed that there was the possibility that the flow could form a single circulation in only one half of the tank. In these instances the other side of the tank would be a large dead area. Mixing cannot be assured Significant dead areas may occur.	Consider lithium's to assess current performance and dead areas. Alternatively consider (e) if flow is intermittent, where mixing is achieved more rapidly and dead areas are minimised. Retrofit (a) only **if continuous inlet and outlet flow is assured** . (b) May be considered if a high level inlet can be used. Selection should be based upon operational constraints and performance.

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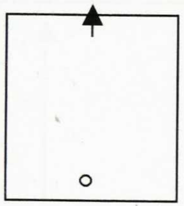
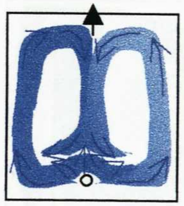
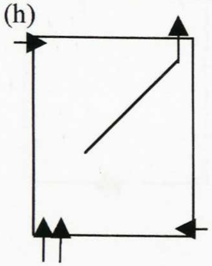
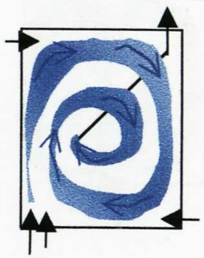
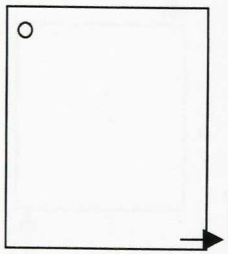
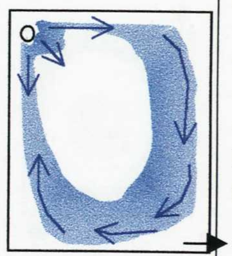
(g) 	**Inlet** : Upturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite, mid wall		Strong tendency for flow to short circuit around the outside wall. With slower moving flow through the middle. Flow spreads out radially from the inlet Highest velocities across the base of the tank Can occasionally be small dead areas in the centre of each recirculation. ✓ Good mixing Poor time for complete water exchange Baseline performance does not deteriorate with intermittent flow.	Simplest solution may be to retrofit (e) non-return valves may be used to maintain head in upstream processes. All performance parameters should be considered. While (a) has the best performance **only if flow into and out of the tank is continuous for all current and future operational regimes.** Retrofit (b) will require a lot of pipework modifications
(h) 	**Multiple inlets** : Horizontal straight pipe inlets at base level, all parallel to side wall all pointing in clockwise (or anticlockwise) direction **Outlet**: Horizontal straight pipe, at base level, from centre of tank		Strong recirculation flow pattern, flow spirals into central outlet. Relies upon some level of continuous inlet and outlet flow to maintain performance ✓ No dead areas. ✓ Most rapid complete water exchange ✓ Good degree of mixing **If outlet flow not continuous reverts to example (L) and performance deteriorates. Percentage inlet flow should ideally be >50%**	No retrofit required **Tank should operate with some degree of continuous inlet / outlet flow**
(i) 	**Inlets:** Downturned bellmouth below TWL, close to the base of tank **Outlet**: Horizontal straight pipe Inlet diagonally opposite. Outlet		Flow spreads out radially from the inlet Greater short circuiting occurs along the walls than (b) Small dead area in the centre of the tank can occur. ✓ Reasonable mixing ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow.	Retrofit (a) **only if continuous inlet and outlet flow.** Alternatively consider (e) if flow is intermittent, where mixing is achieved more rapidly and dead areas are minimised. (b) may be considered if a high level inlet can be used. This would involve the least pipework modifications.

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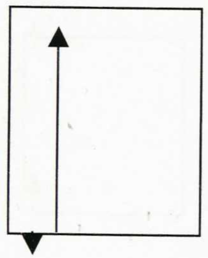
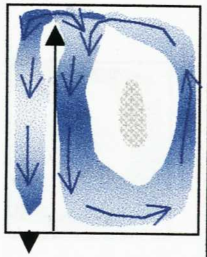
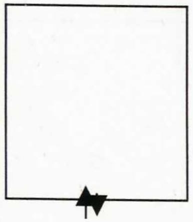
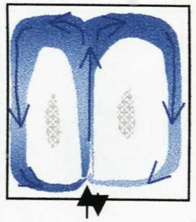
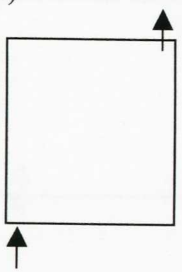
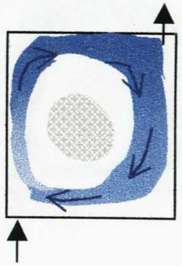
(j) 	**Inlet** : submerged horizontal straight pipe, across the base of the tank **Outlet**: Horizontal straight pipe, possibly in sump Inlet discharges into opposite wall		Flow discharges into the wall then splits. Forming a large dominant circulation cell and a smaller cell, which turns and joins the larger cell. Similar performance to example (L) Some short circuiting Significant central dead area. Long times to achieve complete water exchange Flow pattern similar to (L) with smaller central dead area	Consider (e) where mixing is achieved more rapidly and dead areas are minimised. Retrofit (a) **if continuous inlet and outlet flow only.** (b) May be considered if a high level inlet can be used. Selection should be based upon operational constraints and performance.
(k) 	**Inlet**: Submerged horizontal straight pipe. **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet adjacent mid wall		The inlet jet progresses through the middle of the tank and forms two circulation cells. Small quiescent areas may be found in the centre of each circulation. The size will depend upon the aspect ratio of the tank. The inlets should be parallel to the longest side to minimise dead areas. Mixing is rapid The degree of mixing is good Some short-circuiting occurs. Multiple inlets can be arranged in a similar manner. **Performance severely compromised when outlet flow is greater than inlet**	Ensure that inlet flow is turbulent and inlet duration is sufficient to achieve complete mixing in the tank. Retrofit (a) if continuous inlet and outlet flow for current and future operation.
(L) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally opposite		Inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. Large central dead area, older water, settlement will occur. Some flow will short circuit to the outlet, dilution slightly better than example (m) below. Central dead area will not be completely flushed when tank level is dropped. Poor overall mixing Long times to achieve complete water exchange	Retrofit (a) **if continuous inlet and outlet flow.** Alternatively consider (e) where mixing is achieved more rapidly and dead areas are minimised. (b) may be considered if a high level inlet can be used. Selection should be based upon operational constraints and performance.

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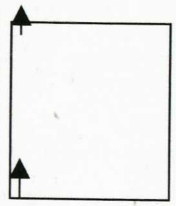
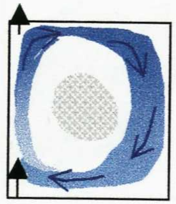
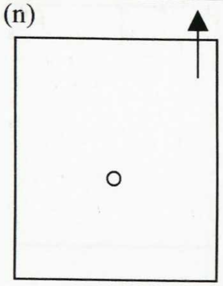
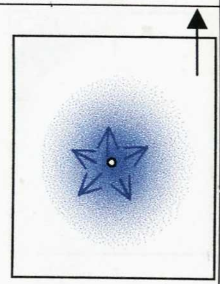
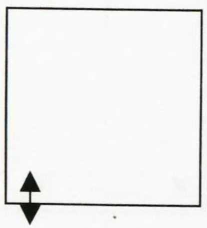
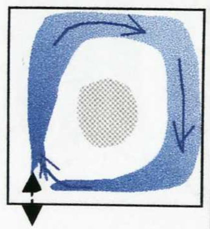
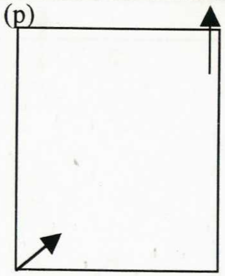
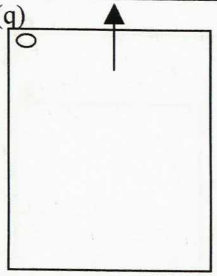
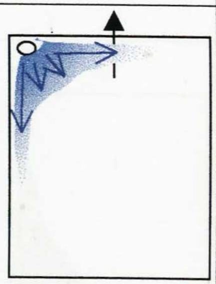
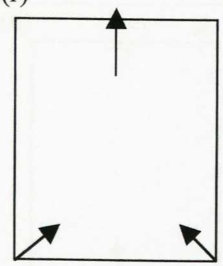
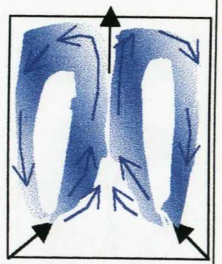
(m) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		Inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. Large central dead area, older water, settlement will occur. Some flow will short circuit to the outlet, poor dilution Central dead area will remain when the level is changed in the tank Poor overall mixing Long times to achieve complete water exchange	Retrofit (a) **only if continuous inlet and outlet flow.** Alternatively consider (e) if flow is intermittent. Mixing is achieved rapidly and dead areas are minimised. (b) May be considered if a high level inlet can be used. Selection should be based upon operational constraints and performance.
(n) 	**Inlet:** Upturned bellmouth at floor level in central position. **Outlet**: Horizontal straight pipe in corner.		Flow jets up to the surface and spreads out radially. Highest velocities across the surface Slower moving flow around the walls. Is likely to lead to greater decay of chlorine residuals as highest concentrations will be across the surface. Not commonly found	Retrofit (a) **only if continuous inlet and outlet flow.** (b) May be considered if a high level inlet can be used. Selection should be based upon operational constraints and performance.
(o) 	**Push Pull** **Common inlet / outlet** Horizontal straight pipe parallel to side wall By design, tank must operate in fill and draw mode		Inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. Large central dead area, older water, settlement will occur. Flow will travel around outside of tank to outlet Central dead area will not be completely flushed when tank level is dropped. Very poor overall mixing Very long times to achieve complete water exchange Inlet flow may not always be turbulent (see section 10)	Retrofit (a) **only if continuous inlet and outlet flow can be assured.** Alternatively consider (e) where flow is intermittent as mixing is achieved more rapidly and dead areas are minimised. (b) May be considered if a high level inlet can be used and flow is intermittent. Selection should be based upon operational constraints and performance.

Appendix D

(p) 	**Inlet**: Downturned 45° bellmouth above TWL, directed towards the centre of the tank **Outlet:** Horizontal straight pipe, possibly in sump Inlet and outlet diagonally opposite		Inlet jet spreads out across the centre of the tank Possibility for dead areas in two corners. Poor mixing Large degree of short circuiting.	Retrofit (a) **only if continuous inlet and outlet flow.**
(q) 	**Inlets:** Upturned bellmouth above TWL. **Outlet**: Horizontal straight pipe, mid wall possibly in sump Inlet and outlet on same wall		Similar flow pattern and performance to (d) Increased short circuiting due to proximity of inlet and outlet If outlet flow is greater than inlet flow this arrangement can lead to large dead area in the corner diagonally opposite the inlet	The distance between inlet and outlet should be maximised (b) should be considered Retrofit (a) may be considered **if continuous inlet and outlet flow and low level inlets may be used**
(r) 	**Multiple Inlets**: Submerged horizontal straight pipe. Angled at 45° towards the centre of the tank **Outlet**: Horizontal straight pipe, mid wall possibly in sump		Where momentum from each inlet is equal mixing is good and rapid. However complex flow patterns result when momentum is not equal. Complex flow patterns Performance highly dependant upon relative inlet flows Likely to result in dead areas Performance erratic dependent upon operation	Retrofit (h) if continuous inlet and outlet flow. Alternatively consider (e) where mixing is achieved more rapidly and dead areas are minimised. In which case both inlets need to be relocated to behave as one inlet next to the main inlet.

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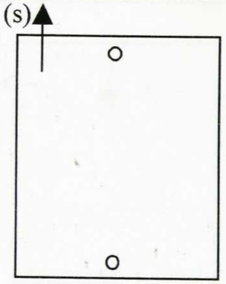
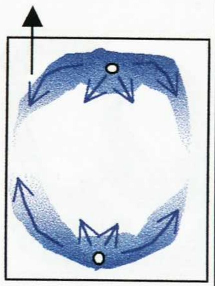
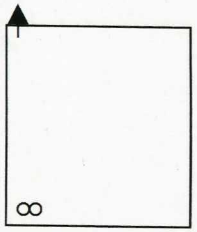
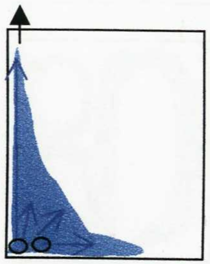
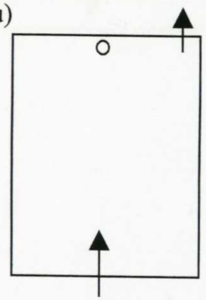
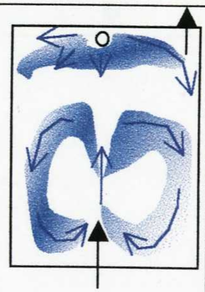
(s) 	**Inlets:** Upturned bellmouth inlets above TWL, mid wall, directly opposite **Outlet**: Horizontal straight pipe		Complex flow patterns Performance is dependent upon the relative inlet flows from both inlets Slow moving flow in the centre of the tank. The central area may then be flushed periodically depending upon operation. Short circuiting is likely Performance is not robust with respect to operational changes.	Retrofit (b) or (c) Ideally the inlet flows should be combined before they enter the tank. Such that only a single inlet exists within the tank. Alternatively the inlet flows can be combined within the tank in a high-level overflow weir. If low level inlets may be used then retrofit (h)
(t) 	**Inlet(s)**: Upturned/ Downturned bellmouths above TWL **Outlet:** Horizontal straight pipe, possibly in sump Inlet and outlet directly or diagonally opposite		Similar flow pattern to (d) However increased short circuiting along the walls Performance will deteriorate however if the inlets are any significant distance apart	Ideally the inlet flows should be combined before they enter the tank. Such that only a single inlet exists within the tank. Alternatively the inlet flows can be combined within the tank in a high-level overflow weir.
(u) 	**Inlets:** Upturned bellmouth & horizontal straight pipe, above TWL **Outlet**: Horizontal straight pipe Inlets directly opposite. Outlet in corner		Complex flow patterns due to multiple inlets Performance highly dependant upon relative inlet flows Short-circuiting from both inlets can occur. Two small quiescent areas can form. Dead areas will periodically be flushed depending upon operation, dirty water incidents taste / odour issues. Not to be recommended	Retrofit (b) or (c) Ideally the inlet flows should be combined before they enter the tank. Such that only a single inlet exists within the tank. Alternatively the inlet flows can be combined within the tank in a high-level overflow weir. If low level inlets may be used then retrofit (h)

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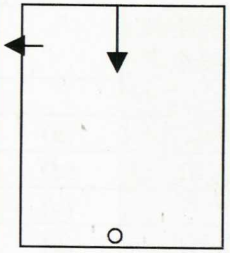
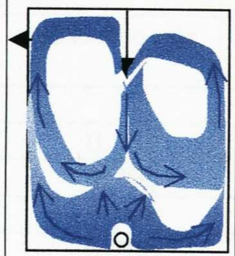
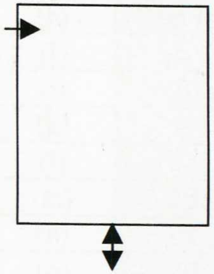
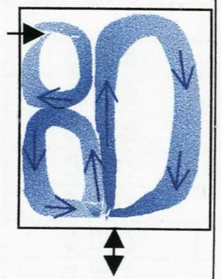
(v) 	**Inlet 1:** horizontal straight pipe, above TWL **Inlet 2:** upturned bellmouth at floor level **Outlet**: Horizontal straight pipe Inlets directly opposite. Outlet in corner		Complex flow patterns Performance highly dependant upon relative inlet flows Likely to result in:- Large dead areas Severe short circuiting Dead areas will periodically be flushed depending upon operation, dirty water incidents taste / odour issues. Not to be recommended	Retrofit (h) if continuous inlet and outlet flow. Consider (e) if flow is intermittent, in which case the second inlet will need to be relocated next to the main inlet. (t) May be considered if a high level inlet(s) can be used. Ideally the inlet flows should be combined before they enter the tank, such that only a single inlet exists within the tank.
(w) 	**Multiple Inlets**: Submerged horizontal straight pipe. **Outlet**: Horizontal straight pipe, possibly in sump		Submerged horizontal straight pipe inlets lead to strong circulation patterns. The dominant circulation cells will be due to the highest momentum inlets. As the flowrate ratios between inlets change the flow pattern will change. This leads to a tank where large dead areas can occur and the performance will change as a function of operation. Not to be recommended	Consider (e) where mixing is achieved more rapidly and dead areas are minimised. In which case both inlets need to be relocated to behave as one. Retrofit (a) **only if continuous inlet and outlet flow**

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	Performance Parameters				Water exchange Times						
	% Dead Volume	% short-circuiting	Mixing achieved	Time to mix	t_0	t_{10}	t_{50}	t_{70}	t_{80}	t_{90}	t_{100}
(a)	0	1.1	0.08	0.309	0.02	0.15	0.74	1.28	1.83	2.26	4.61
(b)	0	5.9	0.14	0.298	0.02	0.10	0.80	1.41	1.95	3.26	
(c)	0	7.3	0.33	0.40	0.10	0.35	2.91	5.05	7.48		
(d)	0	10.8	0.30	0.305	0.05	0.24	1.26	2.25	3.23	3.62	
(e)	4	13.4	0.08	0.298	0.01	0.02	0.96	2.10	3.67		
(f)	0	0.0	0.15	0.076	0.04	0.22	1.33	3.43			
(g)	0	1.8	0.14	0.245	0.05	0.17	1.45	4.44			
(h)	See (a)										
(I)	5	0.0	0.09	0.308	0.09	0.19	0.82	1.40	1.95	3.63	
(j)	8	8.3	0.23	0.330	0.02	0.14	1.27	4.02			
(k)	9	1.0	0.15	0.056	0.001	0.15	0.90	1.64	2.37	5.18	
(l)	11	7.6	0.131	0.231	0.007	0.08	0.87	1.83	3.30	3.81	6.65
(m)	16	8.8	0.12	0.301	0.005	0.09	1.06	2.28	4.18		
(n)	27	0.0	0.14	0.083	0.021	0.16	1.21				
(o)	28	0.3	0.15	0.333	0.004	0.12	1.02	1.88	3.01		
(p)	0	20.0	0.45	0.400	0.065	0.20	1.06	1.86	2.58		
(q)	4	31.4	0.31	0.714	0.005	0.02	1.58	4.41	6.01		
(r)	0	6.7	0.19	0.230	0.035	0.15	1.1	2.07	2.95	4.98	
(s)	0	2.8	0.10	0.800	0.055	0.22	1.33	2.26	3.00	>4.2	
(t)	0 to17	0.63 to 6.42	0.10 to 0.12	0.506 to 0.605	0.08 to 0.13	0.3 to 0.46	1.33 to 2.45	2.14 to 3.68	2.7 to 6.34	3.6 to >8	5.28 to >10
(u)	0 to 23	0.22 to 20.44	0.084 to 0.1	0.216 to 0.42	0.01 to 0.06	0.05 to 0.22	0.63 to 1.32	1.2 to 3.53	1.69 to 4.14	2.72 to >6	
(v)	0 to 36	1.25 to 13.48	0.07 to 0.25	0.12 to 0.15	0.02 to 0.07	0.14 to 0.15	0.72 to 2.83	1.3 to n/a	1.73 to n/a	2.5 to n/a	3.96 to n/a

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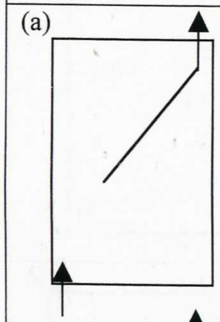
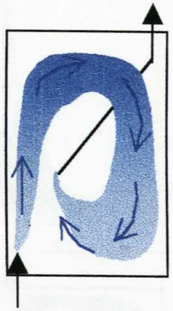
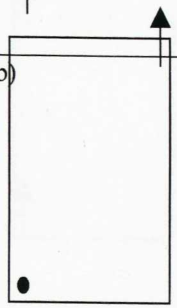
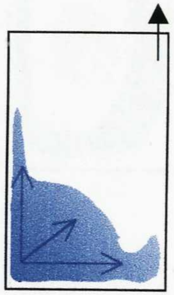
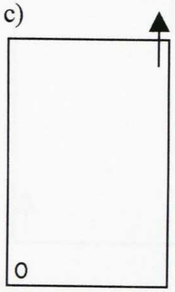
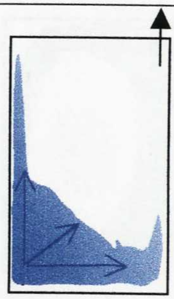
Section 4.5:Tanks / Compartments with Aspect ratios of 1:5 to 1.8:1

Schematic	Description	Flow Pattern and Tank Performance Bar Chart Water age distribution	Performance criteria
(a) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, from centre of tank	 Strong recirculation flow pattern, flow spirals into central outlet. Relies upon some level of continuous inlet and outlet flow to maintain performance There is a deterioration of the performance as the aspect ratio increases towards 1.8:1 Increasing short-circuiting to the outlet occurs off the third wall. **If outlet flow not continuous reverts to example (dii) and performance deteriorates**	No retrofit required **The tank should be operated with continuous flow** If this does not occur then at least oldest water will be taken out first
(b) 	**Inlet** : Downturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite	 Flow spreads out radially from the inlet Highest velocities across the base of the tank Some short circuiting occurs along the walls Slowest moving flow sometimes in the centre of the tank, Good mixing ✓ No significant dead areas ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow. **Performance improves as the aspect ratio increases.**	Best performance of a high level inlet No retrofit required
(c) 	**Inlet** : Upturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite	 Flow spreads out radially from the inlet Highest velocities across the base of the tank Short circuiting occurs along the walls Can occasionally be small dead area in the centre of the tank. Baseline performance does not deteriorate with intermittent flow. **Performance improves as the aspect ratio increases.**	If aspect ratio >1.7: 1 then no retrofit required If aspect ratio <1.7:1 then may be retrofitted as in (b) although improvement should be considered marginal

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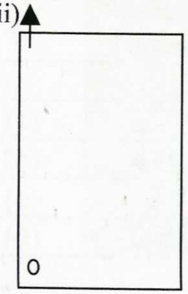
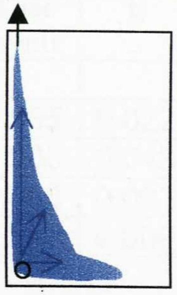
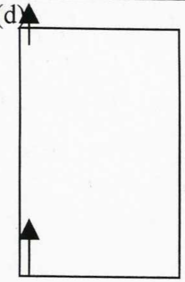
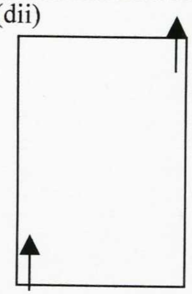
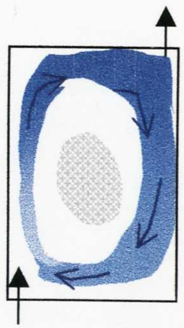
Schematic	Description	Flow Pattern	Bar Chart Water age distribution	Retrofit
(cii) 	**Inlet** : Upturned bellmouth above TWL **Outlet:** Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		Flow spreads out radially from the inlet Highest velocities across the base of the tank Short circuiting is reduced as the aspect ratio increases Dead area in the centre of the tank is eliminated as aspect ratio increases. Baseline performance does not deteriorate with intermittent flow. Performance improves as aspect ratio increases	Consider maximising the distance between inlet and outlet I.e. Outlet diagonally opposite as in (b) or (c)
(d) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		Inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. Large central dead area, older water, settlement will occur. Some flow will short circuit to the outlet, poor dilution Central dead area will remain when the level is changed in the tank Poor overall mixing Long times to achieve complete water exchange Dead areas reduce as aspect ratio increases	If aspect ratio <1.7:1and inlet and outlet flow is continuous and future operation in this manner can be assured consider retrofit as in (a) If inlet flow is intermittent and high level inlets cannot be used consider 4.4 (e). the inlet should be parallel to the longest wall to minimise dead areas If high level inlets may be used retrofit as in (b)
(dii) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally opposite		Inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. Large central dead area, older water, settlement will occur. Some flow will short circuit to the outlet, dilution slightly better than example (d) above Central dead area will not be completely flushed when tank level is dropped. Poor overall mixing Long times to achieve complete water exchange Dead areas are reduced as aspect ratio increases	If aspect ratio <1.7:1 and inlet and outlet flow is continuous consider retrofit as in (a) If inlet flow is intermittent and high level inlets cannot be used consider 4.4 (e). the inlet should be parallel to the longest wall to minimise dead areas If high level inlets may be used retrofit as in (b)

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	% Dead Volume	% short-circuiting	Mixing achieved	Time to mix	t_0	t_{10}	t_{50}	t_{70}	t_{80}	t_{90}	t_{100}
(a)	6.7	3.1	0.12	0.235	0.022	0.123	0.667	1.137	1.502	2.110	4.483
(b)	4.0	11.8	0.12	0.308	0.043	0.134	0.764	1.306	1.770	2.812	4.415
(c)	0	9.5	0.27	0.300	0.093	0.229	0.972	1.627	2.214	3.172	5.936
(d)	9.5	8.5	0.25	0.198	0.009	0.066	0.676	1.161	1.522	2.089	4.262

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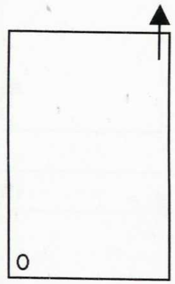
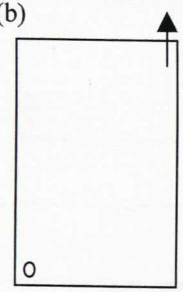
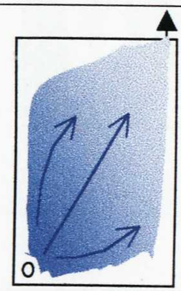
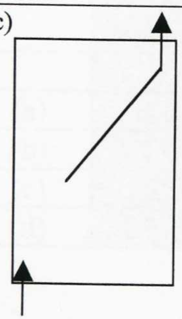
Section 4.6:Tanks / Compartments with Aspect ratios of >1.8:1 to <2.8:

Schematic	Description	Flow Pattern and Tank Performance Bar Chart Water age distribution		Performance criteria
(a) 	**Inlet** : Upturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Short-circuiting along the walls increasing as aspect ratio increases. Resulting in formation of two circulation cells in the tank. Flow pattern shown is for aspect ratio 1.78:1. Highest velocities across the base of the tank ✓ Good mixing ✓ No significant dead areas ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow but changes marginally with aspect ratio.	No retrofit required
(b) 	**Inlet** : Downturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Flow spreads out radially from the inlet Highest velocities across the base of the tank Short-circuiting along the walls is greater than in (a) but decreases with increased aspect ratio. ✓ Good mixing ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow.	Performance would be marginally better if inlet arrangement was changed to (a)
(c) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, from centre of tank		As the aspect ratio increases Flow begins to spiral into the outlet from the third wall Short circuiting occurs Large dead areas occur Performance deteriorates with increasing aspect ratio Not to be recommended at this aspect ratio. **The flow pattern is not stable with respect to intermittent flow**	This design is inappropriate at this aspect ratio. Performance would be better with high level inlet as in (a)

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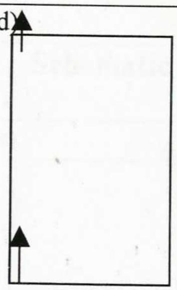
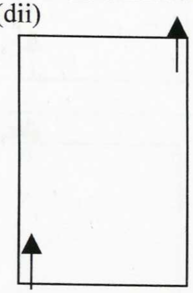
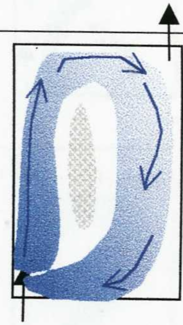
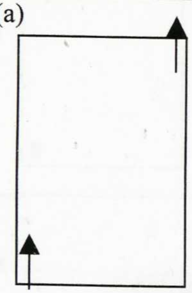
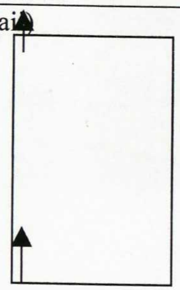
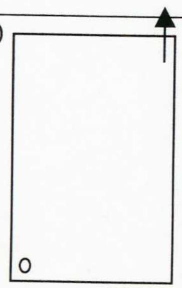
(d) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		Inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. Large central dead area Some flow will short circuit to the outlet, poor dilution Central dead area will remain when the level is changed in the tank	Performance will be better with high level inlets as in (a)
(dii) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally opposite		Inlet jet establishes a strong recirculation flow pattern around the circumference of the tank. Large central dead area, older water, settlement will occur. Some flow will short circuit to the outlet, poor dilution Central dead area will remain when the level is changed in the tank Dead area is reduced over area in square tank due to change in aspect ratio Poor overall mixing Long times to achieve complete water exchange	Performance would be better with a high level inlet as in (a)

	% Dead Volume	% short-circuiting	Mixing Achieved	Time to mix	t_0	t_{10}	t_{50}	t_{70}	t_{80}	t_{90}	t_{100}
(a)	0.0	4.6	0.13	0.401	0.139	0.270	1.148	1.912	2.545	3.618	> 5
(b)	0.0	15.6	0.104	0.262	0.067	0.190	0.793	1.317	1.709	2.249	3.761
(c)	22.9	6.2	0.17	0.191	0.030	0.095	0.647	1.194	1.702	3.436	n/a
(d)	28.3	10.0	0.38	0.219	0.013	0.056	0.574	0.983	1.258	1.630	2.227

Section 4.7: Tanks / Compartments with Aspect ratios of >2.8

Schematic	Description	Flow Pattern and Tank Performance Bar Chart Water age distribution		Performance criteria
(a) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally opposite		Inlet jet establishes multiple circulation's around the tank. A figure of "8" flow pattern is established. ✓ Good mixing ✓ Reasonable time for complete water exchange Triple circulation's can be found as the aspect ratio increases Some short circuiting occurs Small dead areas can occur in the centre of major circulation's.	No retrofit required
(ai) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		Inlet jet establishes multiple circulation's around the tank. A figure of "8" flow pattern is established. ✓ Good mixing ✓ Reasonable time for complete water exchange Triple circulation's can be found as the aspect ratio increases Some short circuiting occurs Small dead areas can occur in the centre of major circulation's.	No retrofit required, unless reduction in short circuiting becomes and issue
b) 	**Inlet** : Upturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Short-circuiting along the walls begins to decrease as the aspect ratio increases. The twin circulation cells in the (shown for aspect ratio 2.8:1) become less dominant, with increased flow through the centre of the tank. Highest velocities across the base of the tank ✓ Good mixing ✓ No significant dead areas ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow but changes marginally with aspect ratio.	Retrofit with (a)

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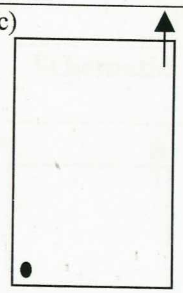
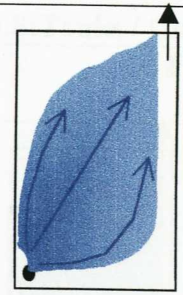
(c) 	**Inlet** : Downturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Flow spreads out radially from the inlet Highest velocities across the base of the tank A dead area occurs in one corner Poor mixing in opposite corner to inlet	Retrofit with (a)

	% Dead Volume	% short-circuiting	Mixing achieved	Time to mix	Dispersion	t_0	t_{10}	t_{50}	t_{70}	t_{80}	t_{90}	t_{100}
(a)	1.8	7.6	0.082	0.194	1869.9	0.018	0.094	0.787	1.402	1.889	2.790	3.428
(b)	0.0	0.0	0.326	0.425	3485.6	0.156	0.437	1.302	2.043	2.615	3.455	5.070
(c)	0.0	17.7	0.488	0.571	2533.0	0.095	0.243	0.992	1.593	2.043	2.776	4.556

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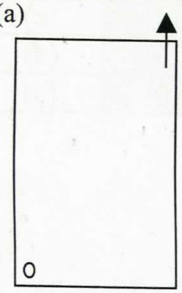
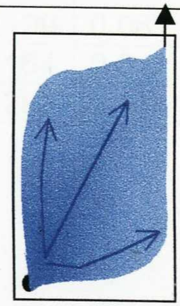
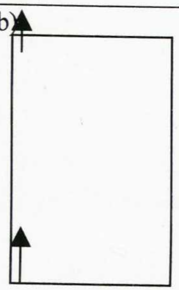
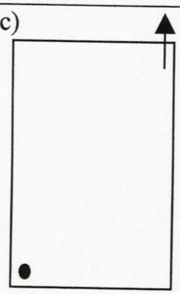
Section 4.8: Tanks / Compartments with Aspect ratios of >3.8:1

Schematic	Description	Flow Pattern and Tank Performance Bar Chart Water age distribution		Performance criteria
(a) 	**Inlet** : Downturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Flow spreads out radially from the inlet, plug flow from inlet to outlet, re-circulation eliminated Highest velocities across the base of the tank Short circuiting along the walls is minimised ✓ Good mixing ✓ Reasonable time for complete water exchange Baseline performance does not deteriorate with intermittent flow. Small dead area may occur in the corner directly opposite inlet.	No retrofit required
(b) 	**Inlet** : Horizontal straight pipe parallel to side wall **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet directly opposite		Inlet jet establishes multiple circulations around the tank. A figure of "8" flow pattern is established Triple circulation's can be found as the aspect ratio increases Some short circuiting occurs Small dead areas can occur in the centre of major circulations.	If high level inlets can be used retrofit as in (a)
(c) 	**Inlet** : Upturned bellmouth above TWL **Outlet**: Horizontal straight pipe, possibly in sump Inlet and outlet diagonally Opposite		Flow spreads out radially from the inlet Highest velocities across the base of the tank A dead area occurs in one corner	Retrofit as in (a)

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	% Dead Volume	% short-circuiting	Mixing Achieved	Time to mix	t_0	t_{10}	t_{50}	t_{70}	t_{80}	t_{90}	t_{100}
(a)	3.3	0.0	0.07	0.199	0.081	0.192	0.756	1.307	1.796	2.991	n/a
(b)	2.3	4.2	0.09	0.164	0.017	0.120	0.794	1.421	1.972	3.040	n/a
(c)	10.9	0.0	0.16	0.285	0.131	0.245	0.767	1.385	2.091	n/a	n/a

SECTION 5.
CIRCULAR TANKS

Information you will need to know to proceed:

- ❑ Tank Diameter
- ❑ Tank Depth
- ❑ The number of inlets and outlets
- ❑ Each inlet type, size and position
- ❑ Each outlet type, size and position.

5.1 Calculate the Tank Diameter to depth ratio.

The results presented here are based upon circular tanks, and not tanks that have been classified as water towers. The results presented in the subsequent ection apply to tanks where the diameter to operational depth ratio during the tests ranged from 5.3 :1 to 17 :1._ If the Tank depth to tank diameter ratio is much less than 5:1 then it likely that much stronger three dimensional flows would exist in the full scale. Hence the results maybe a poor representation of the complexity of the flow patterns in the full-scale reservoir.

In section 5.2, 5.3 schematics will be used to describe the inlet and outlet arrangements. Select the section which best describes your individual tank / compartment. The flow patterns and hydraulic performance of the tank for this configuration will be given.

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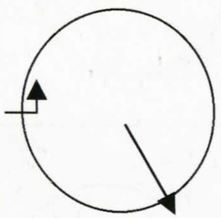
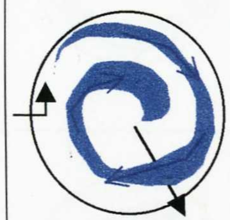
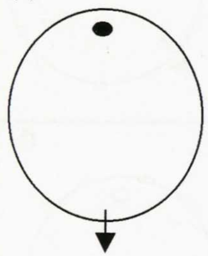
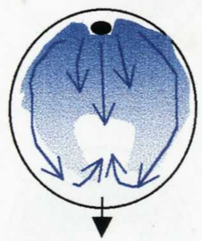
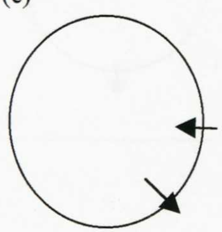
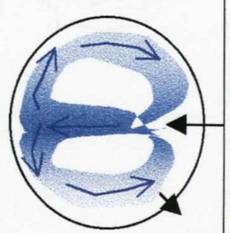
Section 5.2:Circular tanks without dividing walls

Schematic	Description	Flow Pattern and Tank Performance Bar Chart Water age distribution		Retrofits
(a) 	**Inlet:** Horizontal pipe angles around the circumference of the tank **Outlet:** Horizontal straight pipe at base level from centre of tank.		Strong recirculation pattern. Flow spiral into central outlet Continuous flow required to maintain performance No dead areas Good mixing Rapid complete water exchange Negligible short circuiting	Best performance when operated with continuous in/ out flow Operational optimisation only may be required. **Do not consider if intermittent flow regimes are used.**
(b) 	**Inlet:** 45°downturned bellmouth above TWL. **Outlet:** Horizontal straight pipe at base level Inlet and outlet directly opposite		Inlet jet plunges to the base of the tank and flow begins to spread out radially from the point of injection. Some flow short circuits along the circumferential wall. Slower moving water through the centre, some recirculation back through centre. Good mixing No significant dead areas, good water exchange	Best performance when operated with continuous in/ out flow Operational optimisation only may be required.
(c) 	**Inlets** Horizontal straight pipe **Outlets:** Horizontal straight pipes at base level. Inlet not at the maximum distance from the outlet		Inlet jets across the middle of the tank and splits forming two recirculation cells No short circuiting Small dead areas in the centre of each circulation cell Good mixing, good water exchange Rapid mixing Flow pattern can be biased by the position of the outlet in times when the outlet flow is much greater than the inlet flow.	Retrofit as in (a) **if the inlet flow is continuous and can be assured**

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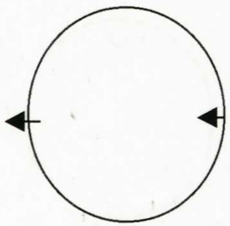
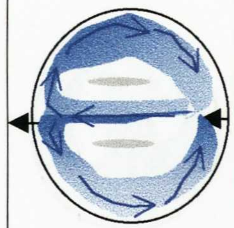
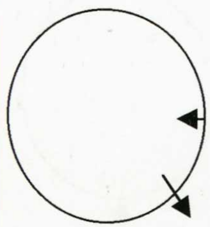
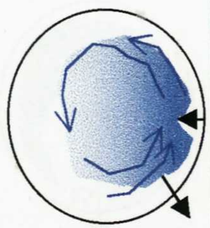
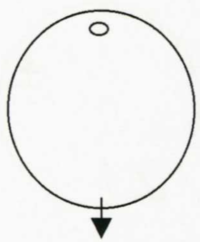
(d) 	**Inlet:** Horizontal straight pipe at base level. **Outlet:** Horizontal straight pipe at base level. **Inlet and outlet directly opposite**		Flow short circuits through the centre of the tank to the outlet Twin circulation cells formed Small dead areas in the centre of each circulation Some short-circuiting. Good mixing. Rapid mixing.	consider (a) if short circuiting and dead areas result in water quality problems, although **flow in and out of the tank must be continuous**
(e) 	**Inlet:** 45°downturned bellmouth above TWL. **Outlet:** Horizontal straight pipe at base level.		Inlet jet plunges to the base of the tank and flow begins to spread out radially from the point of injection. Rapid mixing across the whole of the tank Good mixing. Some short circuiting due to close proximity of outlet Flow pattern can be biased by the position of the outlet in times when the outlet flow is much greater than the inlet flow increasing dead areas.	Relocate outlet to furthest point in tank
(f) 	**Inlet:** Upturned bellmouth above TWL. **Outlet:** Horizontal straight pipe at base level. **Inlet and outlet directly opposite**		Inlet jet plunges to the base of the tank and flow begins to spread out radially from the point of injection. Some flow short circuits along the circumferential and central dividing wall Slower moving water initially through the centre. Recirculation back through centre of the tank. Good mixing Potential for either large central dead area, or twin dead areas.	As inlet is high level consider modification of inlet as in (b) with inlet at maximum distance from outlet

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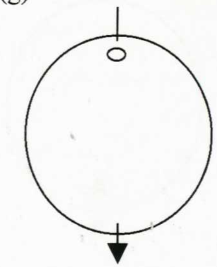
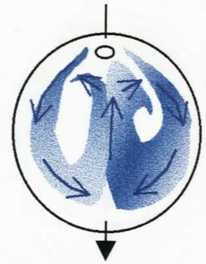
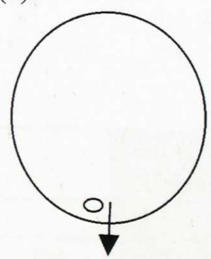
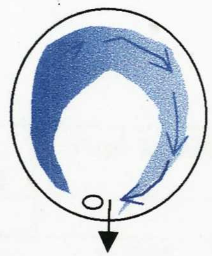
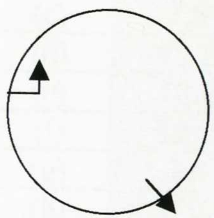
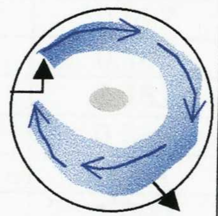
(g) 	**Inlet** :Upturned bellmouth inlet in the base of the tank **Outlet:** Horizontal straight pipe at base level. **Inlet and outlet directly opposite**		Flow rises from the inlet and spreads out across the surface of the tank. Strong circulation patterns around the circumference of the tank in both directions are formed. Resulting in two small dead areas. Large degree of short-circuiting	Retrofit as in (a) **only if in/ outlet flow is continuous** or (b) if inlet / outlet flow is intermittent
(h) 	**Inlet:** Upturned bellmouth above TWL **Outlet:** Horizontal straight pipe at base level. Inlet and outlet adjacent		Large short circuit due to close proximity of outlet Outlet position causes flow from inlet to progress in one direction around circumference. When no outlet flow, flow pattern changes to (f). Tank performance not stable with respect to changes in flow and operation. Possibility of storage of older water and release of water as a plug as a result of changes in operation.	Retrofit as in (b) maximise the distance between inlet and outlet
(I) 	**Inlet** :Horizontal straight pipe parallel to side wall **Outlet:** Horizontal straight pipes at base level.		Very strong circulation around the circumference of the tank. Highest velocities around the outside Large dead area in the middle Short circuiting Extremely poor mixing Poor water exchange	Retrofit as shown in (a)

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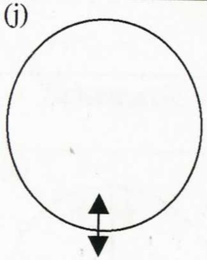
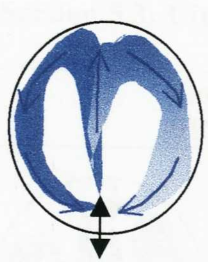
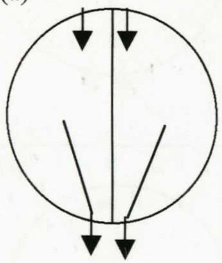
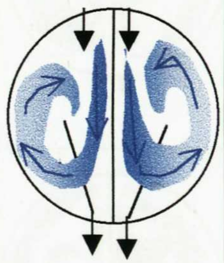
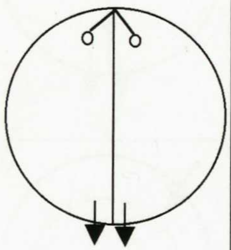
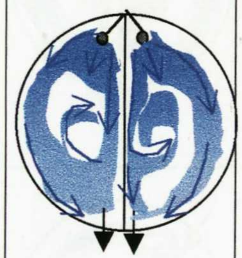
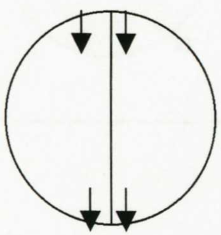
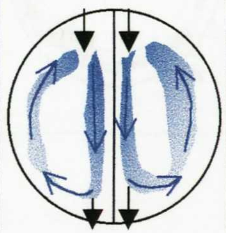
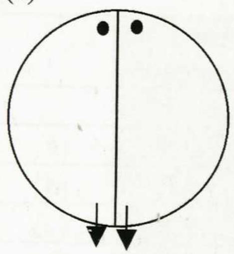
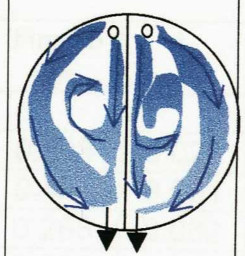
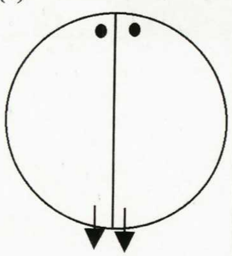
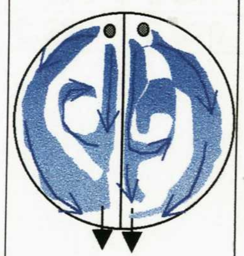
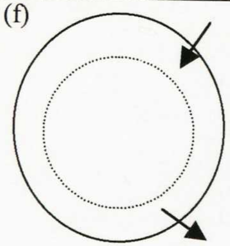
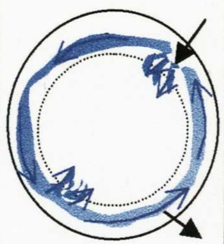
(j) 	**Inlets :**Horizontal straight pipe **Outlets:** Horizontal straight pipes at base level. Inlet and outlet adjacent/Common pipe		Inlet jets across the middle of the tank and splits forming two recirculation cells Small dead areas in the centre of each circulation cell	Retrofit as in (b) if a high level inlet can be used. If this does not effect the frequency of flow entering the tank.

	% Dead Volume	% short-circuiting	Mixing Achieved	Time to mix	t_0	t_{10}	t_{50}	t_{70}	t_{80}	t_{90}	t_{100}
(a)	0.3	2.8	0.15	0.555	0.067	0.141	0.535	0.969	1.308	1.847	3.738
(b)	0.0	3.8	0.17	0.105	0.006	0.105	0.739	1.281	1.700	2.410	5.928
(c)	7.0	0.1	0.11	0.097	0.031	0.103	0.680	1.177	1.559	2.168	3.825
(d)	13.5	3.4	0.13	0.105	0.010	0.113	0.630	1.047	1.365	1.909	6.391
(e)	16.2	4.8	0.09	0.152	0.008	0.084	0.580	0.994	1.317	1.845	3.569
(f)	26.8	6.7	0.14	0.349	0.050	0.081	0.470	0.913	1.251	1.787	3.903
(g)	9.9	15.7	0.19	0.211	0.029	0.072	0.773	1.432	2.026	3.485	
(h)	0.0	20.2	0.12	1.000	0.002	0.013	0.725	1.417	1.917	2.727	5.249
(I)	39.2	11.4	0.80	0.395	0.019	0.049	0.446	0.929	1.446	3.242	

Section 5.3: Circular tanks with dividing walls

Schematic	Description	Flow Pattern and Tank Performance Bar Chart Water age distribution		Performance criteria
(a) 	**Inlets :**Horizontal straight pipe adjacent to central dividing wall **Outlets:** Horizontal straight pipes at base level. **Outlet from centre of tank**		Strong circulation's flow pattern in both compartments Flow spirals into central outlets Relies upon some level of continuous flow in and out to maintain performance Negligible dead areas Reasonable mixing Some short-circuiting	No retrofit required flow should be continuous
(b) 	**Inlet:** Downturned bellmouth Angled towards centre of compartment **Outlets:** Horizontal straight pipes at base level. Inlet and outlet directly opposite		Some flow short circuits around the sidewalls and along the central dividing walls. The flow travelling around the circumference generally reaching the outlet first The angle of the inlet improves the mixing in the centre of the tank. The flow travelling down the central wall then forms a circulation in towards the centre of the tank. Good mixing, good water exchange	No retrofit required
(c) 	**Inlets :**Horizontal straight pipe adjacent to central dividing wall **Outlets:** Horizontal straight pipes at base level. Inlet and outlet directly opposite		Flow short circuits along central baffle directly to the outlets Strong recirculation flow pattern Dead areas in the centre of each compartment Reasonable mixing, good water exchange Rapid mixing	Retrofit as in (a) if flow is continuous

(d) 	**Inlet:** Upturned bellmouth inlets in each compartment above TWL Mid height wall **Outlets**: Base level outlets Horizontal straight pipes Inlet and outlet directly opposite		Flow short circuits around the side walls and along the central dividing walls. The flow travelling around the outside generally reaching the outlet first The flow travelling down the central wall then forms a circulation in towards the centre of the tank. Large short circuiting Reasonable mixing	Retrofit as in (b)
(e) 	**Inlets:** Downturned bellmouth inlets in each compartment Above TWL Mid height wall **Outlets:** Horizontal straight pipes at base level. Inlet and outlet directly opposite		Flow short circuits around the side walls and along the central dividing walls. The flow travelling around the outside generally reaching the outlet first The flow travelling down the central wall then forms a circulation in towards the centre of the tank. Short circuiting Dead areas in slow moving central regions Reasonable mixing	Retrofit as in (b)
(f) 	**Inlet :**Horizontal straight pipe adjacent to central dividing wall **Outlet:** Horizontal straight pipes at base level. Circular mid height internal wall.		Central baffle submerged Flow travels around outer ring Passes over baffle into central ring. Water exchange between the centre ring and the outside ring is poor. Very large central dead area. Massive short circuiting.	Extend outlet pipe from the centre

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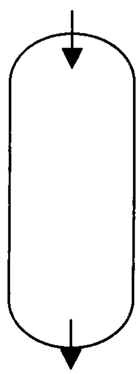
	% Dead Volume	% short-circuiting	Mixing achieved	Time to mix	t_0	t_{10}	t_{50}	t_{70}	t_{80}	t_{90}	t_{100}
(a)	2.0	9.7	0.21	0.303	0.023	0.081	0.634	1.230	1.752	2.802	
(b)	5.4	1.2	0.11	0.451	0.051	0.150	0.711	1.256	1.716	2.658	
(c)	7.2	13.1	0.18	0.266	0.032	0.075	0.642	1.101	1.444	1.962	3.006
(d)	0.0	30.0	0.20	0.500	0.064	0.113	0.777	1.472	2.041	3.100	
(e)	16.3	6.7	0.21	0.536	0.047	0.154	0.694	1.319	1.988		
(f)	48.2	46.5	0.34	0.296	0.020	0.094	0.350	0.702	0.948	1.265	1.731

SECTION 6.
COMPLEX TANK TYPES

Existing service reservoirs may have been designed to fit within an existing site boundary. They may therefore have complex shapes or internal structures.

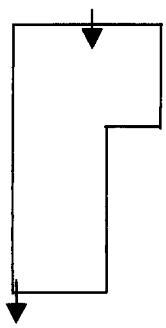
Where a reservoir does not fit neatly into any of the previous categories preliminary evaluation of the design may be made by taking the basic shape of the tank or treating it as a series of composite shapes.

See the two examples given below



This tank while oval can be considered to be predominantly rectangular with rounded corners.

Treating the tank as rectangular, one can therefore determine the aspect ratio and assess the tank accordingly.



This tank may be considered to comprise of two rectangular tanks. The dominant should be considered to be the tank that contains both the inlet(s) and outlet(s).

In this case the larger rectangular section of the tank will determine the performance. A secondary circulation is likely to be induced in the smaller rectangular section of the tank.

If the tank is more complex including angular walls, benching, buttresses or complex or large internal support structures then contact Technical Applications for future advice.

An individual model may be required.

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SECTION 7: BAFFLED TANKS

Although it is recommended that service reservoirs be designed to promote good mixing. If an existing tank already has some internal baffling in good condition. It may be more appropriate to evaluate the plug flow efficiency of the existing tank and recommend retrofits to improve the efficiency rather than remove the existing baffling and try and promote good mixing.

The plug flow efficiency can be evaluated using internal report :

R97/196/B Chlorine Contact Tanks, Hydraulic Performance and Retrofit Manual, July 1997.

North West Water Asset Standards recommend a plug flow efficiency of 60%. This should be achievable with a retrofitted tank. It is unlikely to be attained by the existing design.

The whole life cost of improving the baffles to attain a good plug flow efficiency can be compared with the cost of modification to the inlet / outlets to produce a well-mixed tank.

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SECTION 8

WATER AGE
PERFORMANCE ASSESSMENT

Using the table below fill in the performance characteristics for the individual type of tank, as defined in Sections 3 to 7.

	1. % Dead Volume	2.	3. % short circuiting		4. 50%	5. 70 %	6. 100 %
A				Steady State Water Exchange Parameters			
B	Nominal retention Time T (days)			Real Time for water exchange in days			

The % Dead volume, short circuiting values required in cells A 1 to A3 can be read directly from the performance summary tables in sections 4 and 5.

Steady State Water Exchange Parameters required in cells A 4 to A6 can be read directly from the performance summary tables in sections 4 and 5.

Nominal retention Time T (days) required in cell B3 is as calculated in Section1.

The real Time water age: required in cells B4 to B6 can be calculated by multiplying the steady state performance parameters (A4-A6) by the Nominal retention time (B3). This is a measure of the "real" time it is expected to take for the water to be exchanged in the tank

Now the performance evaluation is complete. One needs to determine if the current level of performance is acceptable. This is done by comparing the performance to standards that have been set for acceptable water age see Table 8.2.

The values for 90% water exchange should be used. 50% water exchange figures should only be used where values for 90% are not given. This generally occurred where the performance of the reservoir was poor.

If the performance is considered unacceptable then recommendations are given.

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% Dead Volume	Time to achieve Water Exchange		Action
	50%	**90%**	
Negligible		5 days	Performance is acceptable **No action required**
Negligible		<10 days	The design is acceptable The water age is too long **Operational optimisation is recommended** **Go to SECTION 9.**
>10%		<10 days	The design can be improved Improving the design may reduce the water age to acceptable levels. Suitable retrofit options should be considered **Go to SECTION 9.**
>10%		>> 10 days	The design is extremely poor Both operational optimisation and suitable retrofit options should be considered. **Go to SECTION 9.**

Table 8.2.

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SECTION 9.
OPERATIONAL OPTIMISATION AND RETROFIT OPTIONS

There are two routes to optimising service reservoir performance: Operational optimisation and retrofit options.

If the tank does not have a significant dead volume then it is likely that the inlet and outlet arrangement are adequate for that particular type of tank, but the operational regime is resulting in much larger water age than is recommended.

If a tank has a significant dead volume then it is likely that the inlet and outlet arrangement are inappropriate for that particular type of tank, this will contribute to much longer water ages.

In most cases where performance is very poor, a combination of both will result in the best outcome.

OPERATIONAL OPTIMISATION

If the nominal retention time is greater than 1 day then operational optimisation should be considered first. There may be security of supply / risk reasons why this is the case. Each site should be considered individually.

The nominal retention time should not be greater than 2 days, unless a very strong case with exceptional circumstances is given for it being so.

RECOMMENDATIONS

- ✓ Flow in and out should be as continuous as possible
- ✓ Flow in should always be turbulent (Section2)

Where nominal retention time is too high, consider:

- ✓ Taking one half of a tank out of service
- ✓ Dropping the operational top water level in the tank
- ✓ re-directing more flow through the tank

For example for push pull systems the main flow could be forced through the tank.

Where nominal retention time is considered excessive; >20 days

Consider replacement of the tank
Consider eliminating the tank

Current and future operational requirements within the distribution zone will need to be considered.

Appendix D

RETROFIT OPTIONS

The retrofit options in this report are focussed on attaining the optimum hydraulic performance with minimal changes to the existing inlet and outlet arrangements.

Suitable retrofit options are defined by the mode of the operation of the tank either continuous / intermittent flow and the general nature / aspect ratio of the tank.

To determine the appropriate retrofit option(s): return to the hydraulic appraisal section, to the relevant sub section which best describes the tank to be improved.

In each section the inlet and outlet arrangements are described in order of performance. For each inlet and outlet geometry suitable retrofits are listed, which you may have made a note of during the initial appraisal.

To evaluate each retrofit look up the performance in both the hydraulic appraisal and the key performance parameter table.

When you have selected what you consider to be the best retrofit, taking into account the limitations on application. Use the Key performance parameters for that geometry and repeat Section 8: to determine if the performance when retrofitted is acceptable.

SECTION 10:

THE INLET FLOW IS NOT TURBULENT
NO MIXING WILL OCCUR

The flow into the tank must be turbulent to achieve any degree of mixing. The only mixing that will occur in the tank with non turbulent inlet flow will results as a function of diffusion.

Under non-turbulent conditions the flow coming into the tank will have some momentum and move away from the inlet as it enters the tank. It will not have sufficient energy to entrain any of the surrounding flow.

It is highly likely that over time thermal stratification will occur in this tank, deposition of any particles in suspension is highly likely and there are likely to be significant dead areas.

Although modelling studies were conducted within these flow regimes the errors predicting performance are anticipated to be large, as the frictional forces within the model would have become more dominant.

The incoming flow would be expected to take a similar path around the tank as would have been predicted by the hydraulic assessment (Section 3 to 6) if the incoming flow had in fact been turbulent. However, the incoming flow would not entrain the surrounding fluid and is more likely to stay as a coherent plug. Therefore predicted dead areas that would normally result from the particular inlet / outlet arrangement and geometry will be much larger.

RECOMMENDATIONS

Option A
Increase the flowrate through the tank to ensure that the flow is turbulent.

If this is feasible then you may wish to determine a realistic flow that may be assured through the tank and **go back to Section 1.**to repeat the appraisal.

Option B
Reduce the diameter of the inlet pipe to ensure that the flow is turbulent at minimum flowrate.

This will incur additional headloss and pressurisation in the upstream main and may impact the flow that can be put through the tank. Alternatively the tank may have been originally sized for much larger flows and therefore downsizing the inlet pipes just prior to discharge may be feasible.

If this is feasible then you may wish to determine a more suitable inlet diameter and **go back to Section 2.** to complete the remainder of the appraisal.

If either of the above are not feasible then one should ensure that the tank does not operate in a last in first out basis and therefore it is recommended that the tank is retrofitted as a plug flow / baffled tank in accordance with internal report :

R97/196/B Chlorine Contact Tanks, Hydraulic Performance and Retrofit Manual, July 1997.

New service reservoirs should never be designed on this basis

Appendix D

APPENDIX 1

SERVICE RESERVOIR AUDIT DOCUMENT

Name of Service Reservoir

District

Address/ Location

Asset Manager

Treatment Controller

A. General Site Information

A1 Are site and tank layout drawings available yes/no
If yes please can you send a copy
If no or different from drawings can you provide a simple sketch

A2 Number of reservoirs on site and connections
Number of compartments, interconnections and volume of each

Reservoir Number	No of Compartments	No of interconnections	Volume of Compartments			
			1	2	3	4

For more than one are they in parallel /cascade/ independent
Any unmetered cross flow between the tanks yes/no

A3 Number of water sources
For multiple sources: water blended together prior entering the tanks yes/no

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For each source

	Flow			pH			Free Cl Residual: mg/l		
Name	Max	norm	min	max	norm	min	max	norm	min

A4 Number of outlets

Is it push-pull operated

For each outlet

Supplying district	**Flow**			**Distance to nearest customer**	**Customer complaints ie taste**
	Max	**Norm**	**min**		

A5 Secondary disinfection yes/no
If yes inlet/outlet
Reason for secondary disinfection

A6 Water quality/bacteriological problems at site yes/no
THM problems at site or in supplied distribution zone yes/ no
Iron problems at site or in supplied distribution zone yes/ no
If yes give details

A7

Are the reservoirs at the end of the distribution system? yes/no
Is it by-passed yes/no
If yes when and why

A8 Prime function of the reservoirs, please rank

Storage / emergency supply of water
Maintain distribution pressure
Flow balancing

A9 General comments

Strategic importance of the site (if failure what consequences)

Maximum shut down period

Are the reservoirs oversized yes/no

Level of priority for refurbishment

Future operational changes planned

Is condition of reservoir known?

Do public have access

Vegetation / trees on reservoir

Access for animals grazing

B. Information related to the construction and integrity of each tank

B Age/year built

B2 Can tanks/compartments be isolated

B3 Underground / above ground
If above ground is tank insulated yes/no
If yes how is the tank insulated

B4 Is the tank open/closed

B5 Material of construction
Brick / Concrete
Lined / unlined
others

B6 Integrity of the tank (i.e. potential for external contamination)

Access hatches
excellent/good/fair/poor
Leakage of ground water
excellent/good/fair/poor
Roof
excellent/good/fair/poor
Ventilators
excellent/good/fair/poor
Ventilator mesh aperture 1 mm< aperture >5mm

B7 Internal condition of the tank (i.e. potential for bacterial growth)
Wall excellent/good/fair/poor
Support column
excellent/good/fair/poor
Baffle walls/curtains (if any)
excellent/good/fair/poor

B8 Conditions of associated pipework and fittings

B9 Inspection and cleaning strategy yes/no
If yes give details

B10 Last inspected on (date)

Last cleaned on (date)

B11 How is the SR drained?

B12 Any depth of sludge on the bottom

C. **Information related to the hydraulics of each tank**

Tank volume

Tank geometry rectangle/square/

circular/other

Style baffled / unbaffled

Internal dimensions

Design water level m

top water level m

bottom water level m

Designed turn over time (time one complete water exchange)

Engineering drawings available yes/no
If yes, could we please have a copy?

If no then could we have a sketch of the internals and connections

If the Engineering drawings are incorrect then we will still require a sketch of internals and connections, showing any differences from drawings

C2 Operational information

	Maximum		**Nominal**		**Minimum**	
	Daily	**Yearly**	**Daily**	**Yearly**	**Daily**	**Yearly**
Top water level						
Total flow in						
Total flow out						

C3 Has a Lithium tracer studies been done yes/no
Has a chlorine step change been done yes/no
If yes please can you give details
If no, is there one planned yes/no

C4 Is there a common inlet/outlet yes/no

C5 Inlets

No of inlets

For each inlet can you complete the following information

		Inlet 1	Inlet 2	Inlet 3
Location				
Height above bottom				
Size				
Water source				
Flow rate	Max			
	Normal			
	Minimum			
Flow control	Float valve			
	Level detector			
	Manual			
Water quality parameters	PH			
	Chlorine			
	Manganese			
	Iron			

Sketch of the inlet area showing pipe diameter, control valves etc

C6. **Outlets**
No of outlets
For each outlet

	Outlet 1	Outlet 2	Outlet 3
Location			
Height above bottom			
Style ie bellmouth			
Diameter			

Sketch of the outlet areas showing diameter, washout channel etc

C7 Detailed arrangement of baffles / compartment walls

Construction material e.g. concrete, PVC sheets

Pressure equalisation holes or gaps at the bottom yes/no

Top of the baffles submerged yes/no
If yes, why

C8 Details of sample point

Location of tap

How is sample delivered?

Length of pipe to tap

Material of pipe

Targets Chlorine residual

Target pH

Are samples logged yes/no

C9 General comments: e.g. effectiveness of mixing, turnover, stratification

Appendix D

D Secondary Disinfection and Monitoring

Dl	Secondary disinfection		
	Reason type (ie: gaseous chlorine, Hypochlorite, on site generation)		
	Injection point	inlet outlet through access hatch	
	Chlorine dosage	maximum normal minimum	
	Mixing	no mixer static mixer	
	Control method	manual / automatic	
	Target residual	mgl	
D2	Chlorine residual sampling		
	Location		
D3	Quality sampling		
	Location Integrity of sampling system good/poor		
D4	Other chemical dosing ie: Lime		
	Purpose Location Dosage		
D5	Level measurement/control		
	Location Equipment Last calibration (date)		

APPENDIX 2: FLOW SPLITTING BETWEEN TWIN COMPARTMENTS

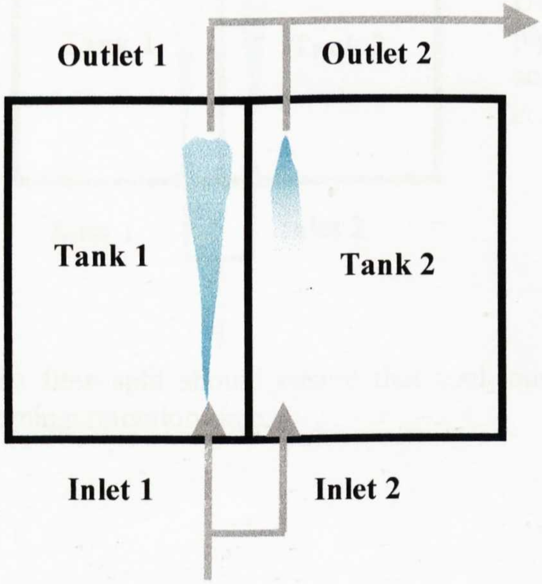
Achieving adequate flow splitting between adjacent tanks or twin compartment tanks is key to ensure that the hydraulic performance of each is equivalent and acceptable.

In many instances insufficient thought has been given to the hydraulic consequences of inlet pipework arrangements.

Below is a simple example of typical inlet / outlet pipework arrangements that can result in water quality and hydraulic control issues.

A common inlet pipe is intended to supply inlets 1 and 2 with equivalent flow. The pipework has been arranged such that there is one common inlet main to the reservoirs and one common outlet main. It is assumed that, as both pipes are similar and of the same diameter as the incoming main, that the flow will split equally into tanks 1 and 2.

As the tanks are linked by common pipework, they should balance, and have the same TWL. So it is assumed that the same flow will enter each through their respective inlets and equivalent flow will leave both tanks through the outlets in response to changes in demand and pressure in the system.



In consequence what often occurs is that the flow travels along the supplying main and progresses directly thorough into Tank 1.

If there is no additional headloss in line 1 and isolation valves are fully open, then most of the flow will go directly into tank no 1.

The level in Tank 1 will rise, resulting in an imbalance between the tanks, such that flow will exit Tank 1 through Outlet 1 and enters Tank 2 via the Outlet 2, until such time as the top water level in the two tanks are equivalent.

Tank 1 takes the full inlet flow and Tank 2 becomes a push pull tank, where what was designated the outlet during the design phase becomes a common inlet / outlet during operation.

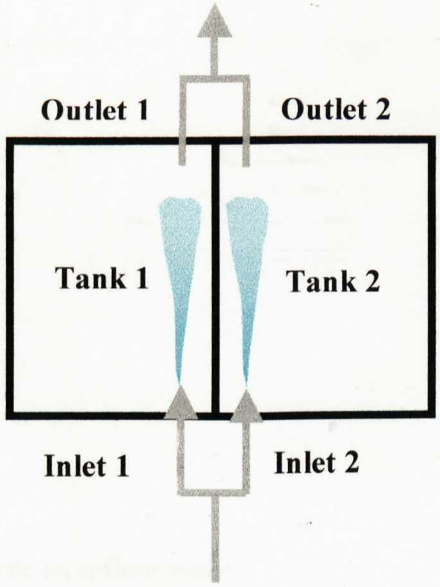
The concern with this scenario is that the water in Tank 1 passes through very rapidly. In contrast to Tank 2 where water is of indeterminate age and quality.

Where the inlet pipework is similar to that described above and that system has not been calibrated with flowmeters to ensure adequate flow is received by both compartment / tanks. Then it should be assumed that one tank / compartment is operating as a push pull tank.

In these instances it is a priority to take action to ensure that the flow split is correct.

Recommendations

- ❑ Use strap on ultrasonic flowmeters to measure the flow into each tank / compartment. Adjust the position of inlet isolation valves to ensure each tank receives adequate flow. This may incur some marginal additional pressurisation on the upstream main.



Design inlet pipework, which is more conducive to flow splitting.

Use differential headloss in the separate inlet pipework to split the flow adequately in accordance with the operational volume of the compartments / tanks.

The flow split should ensure that each tank / compartment has the same operational nominal retention time.

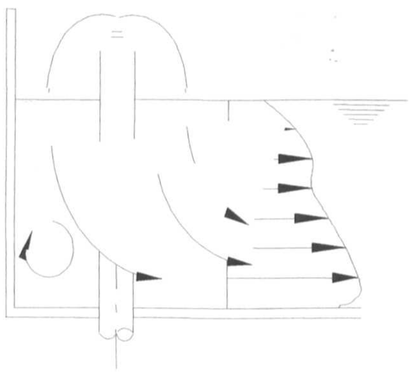
APPENDIX 3:
INLET TYPES

The inlet type is the most dominant single factor which determines the flow pattern in the tank. Most common inlet types results in the highest water velocities being across the base of the tank. Which is why service reservoirs tanks with mid height dividing walls can often be treated as twin connected tanks.

The following sections describe the inlet types and the flow effects that result.

High Level Inlets: Above TWL

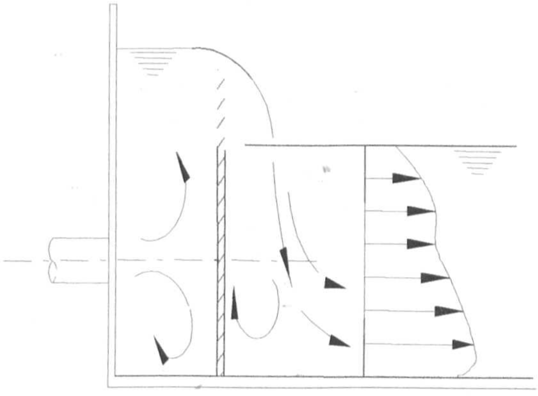
Upturned Bellmouth Inlets:



f)

Free overflow vertical inlet, with Bellmouth above TWL
The annular flow plunges through the surface. The flow initially spreads out radially from the inlet pipe in all directions, with the highest velocities initially across the base of the tank. Some of the momentum of the inlet flow is lost. If the inlet is situated close to sidewalls there can be a tendency for flow to short circuit along the walls.

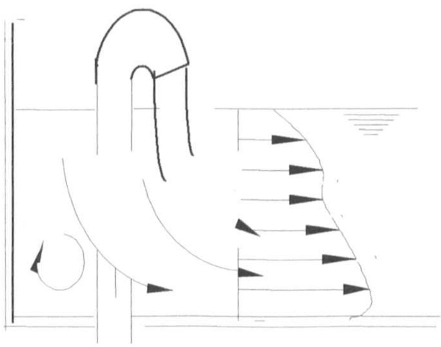
Free overflow weir
Similar to above



(g)

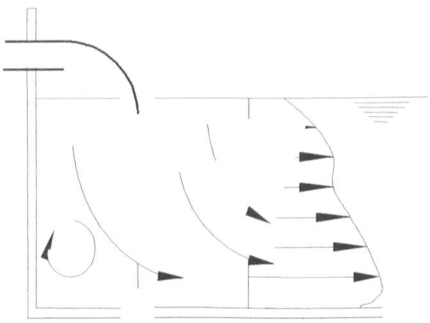
Free overflow weir inlet
Flow plunges through the surface, the highest velocities are across the base of the tank

Downturned Bellmouth inlet



The flow plunges through the surface and initially spreads out radially in all directions from the injection point, with the highest velocities initially across the base of the tank. A similar flow pattern is established to the upturned bellmouth inlet. In this instance much less of the inlet momentum is lost. Therefore the initial radial spread of the flow is consistently more pronounced.
Tracer tests have shown that this inlet shows reduced propensity for severe short-circuiting along adjacent walls than the upturned bellmouth as discussed above.

Horizontal inlet pointing forwards.

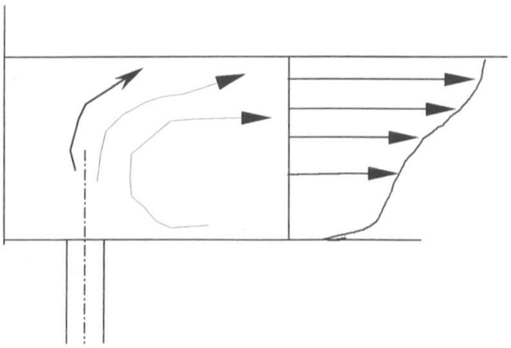


Some of the forward momentum of the inlet jet is lost due gravitational effects. What results is a combination of a forward momentum jet and a downturned inlet jet. So the flow plunges through the surface with a biased directional momentum. The highest velocities are across the base of the tank and the jet also expands radially from the point of injection.

Appendix D

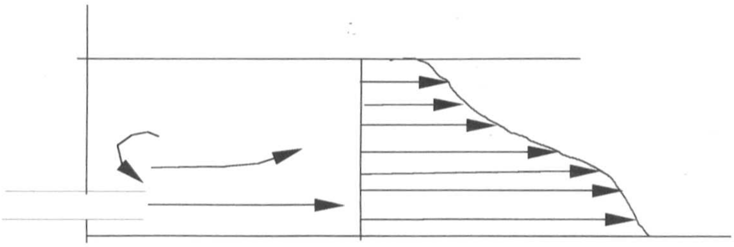
Low Level – Submerged inlets

Horizontal straight pipe inlets



The jet has high forward momentum that is transferred directly into the water. It induces strong re-circulation flows. As the jet expands it entrains surrounding water, which promotes mixing.

Submerged vertical inlet, in floor or base of the tank.



The jet rises to the surface and spreads out radially causing surface streaming. Would not be recommended as highest concentrations of chlorine residual would be across the surface which would promote greater losses.

Inlets of this type would be the major cause of cross over of flow in tanks with central dividing, not full height walls.

Downturned Bellmouth Inlet
Similar performance to the downturned bellmouth above TWL. The discharge point should not be too close the floor as this will increase the velocities across the base of the tank and may cause accelerated localised corrosion at the point of discharge.